Access Network Selection in Heterogeneous Networks

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Abstract

The future Heterogeneous Wireless Network (HWN) is composed of multiple Radio Access Technologies (RATs), therefore new Radio Resource Management (RRM) schemes and mechanisms are necessary to benefit from the individual characteristics of each RAT and to exploit the gain resulting from jointly considering the whole set of the available radio resources in each RAT. These new RRM schemes have to support mobile users who can access more than one RAT alternatively or simultaneously using a multi-mode terminal. An important RRM consideration for overall HWN stability, resource utilization, user satisfaction, and Quality of Service (QoS) provisioning is the selection of the most optimal and promising Access Network (AN) for a new service request. The RRM mechanism that is responsible for selecting the most optimal and promising AN for a new service request in the HWN is called the initial Access Network Selection (ANS). This thesis explores the issue of ANS in the HWN. Several ANS solutions that attempt to increase the user satisfaction, the operator benefits, and the QoS are designed, implemented, and evaluated.

The thesis first presents a comprehensive foundation for the initial ANS in the HWN. Then, the thesis analyses and develops a generic framework for solving the ANS problem and any other similar optimized selection problem. The advantages and strengths of the developed framework are discussed. Combined Fuzzy Logic (FL), Multiple Criteria Decision Making (MCDM) and Genetic Algorithms (GA) are used to give the developed framework the required scalability, flexibility, and simplicity.

The developed framework is used to present and design several novel ANS algorithms that consider the user, the operator, and the QoS view points. Different numbers of RATs, MCDM tools, and FL inference system types are used in each algorithm. A suitable simulation models over the HWN with a new set of performance evolution metrics for the ANS solution are designed and implemented. The simulation results show that the new algorithms have better and more robust performance over the random, the service type, and the terminal speed based selection algorithms that are used as reference algorithms. Our novel algorithms outperform the reference algorithms in terms of the percentage of the satisfied users who are assigned to the network of their preferences and the percentage of the users who are assigned to networks with stronger signal strength. The new algorithms maximize the operator benefits by saving the high cost network resources and utilizing the usage of the low cost network resources. Usually better results are achieved by assigning the weights using the GA optional component in the implemented algorithms.

Declaration

The work contained within this thesis is purely that of the author unless otherwise stated. This thesis has not been submitted as a whole for any examination, qualification or publication.

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To my lovely family.....
To my mother and father.....
To my wife Sabah.....
To my daughter Hanadi.....
To my son Nooraddin.....

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List of Acronyms

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Forth Generation
ABC	Always Best Connected
AI	Artificial Intelligence
AIS	Access and Interface Selection
AN	Access Network
ANS	Access Network Selection
B3G	Beyond 3rd Generation
BER	Bit Error Rate
BoA	Bisector of Area
BS	Base Station
C/I	Carrier-to-Interference ratio
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CoA	Centroid of Area
CRRM	Common Radio Resource Management

dB	Decibel
DoCoMo	Do Communications Over the Mobile Network
DVB	Digital Video Broadcasting
DVB-H	Digital Video Broadcasting-Handheld
DVB-T	Digital Video Broadcasting-Terrestrial
E2R	End-to-End Reconfigurability
EC	European Commission
EDGE	Enhanced Data rates for GSM Evolution
ELECTRE	ELimination and Choice Expressing REality
EVEREST	Evolutionary Strategies for Radio Resource Management in Cellular Heterogeneous Networks
FDD	Frequency Division Duplex
FIS	Fuzzy Inference System
FL	Fuzzy Logic
FLC	Fuzzy Logic Control
GA	Genetic Algorithm
GERAN	GSM EDGE Radio Access Network
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
GUI	Graphical User Interface
HO	Handover
HSDPA	High Speed Downlink Packet Access
HWN	Heterogeneous Wireless Network

IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IST	Information Society Technologies
JAC	Joint Admission Control
JCC	Joint Congestion Control
JLC	Joint Load Control
JRRM	Joint Radio Resource Management
JSC	Joint Scheduling Control
kbps	kilo bits per second
km/hr	kilometer per hour
LB	Lower Bound
LE	Linear Equalities
LI	Linear Inequalities
LOM	Largest of Maximum
MADM	Multi-Attribute Decision Making
MBMS	Multimedia Broadcast and Multicast Services
MCDM	Multiple Criteria Decision Making
MF	Membership Function
MMT	Multi-Mode Terminal
MOM	Mean of Maximum
MS	Mobile Station
ms	millisecond
MSS	Mobile Station Speed

MT	Mobile Terminal
NE	Non-linear Equalities
NGN	Next Generation Network
NGWN	Next Generation Wireless Network
NI	Non-linear Inequalities
NRT	Non Real Time
OP	Operator Preferences
OSA	Operator Software Assistant
PCC	Pearson's Correlation Coefficient
PDR	Propagation Delay Requirements
QoS	Quality of Service
RA	Resources Availability
RAN	Radio Access Network
RAT	Radio Access Technology
RBR	Required Bit Rate
RRM	Radio Resources Management
RSS	Received Signal Strength
RUNE	RUdimentary Network Emulator
SA	Software Assistant
SCC	Spearman's Correlation Coefficient
SCOUT	Smart user-centriC cOmmUnication environmenT

SDR	Software Defined Radio
SIR	Signal to Interference Ratio
SMART	Simple Multi Attribute Rating Technique
SOM	Smallest of Maximum
ST	Service Type
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRUST	Transparently Reconfigurable UbiquitouS Terminal
TT	Terminal Type
UB	Upper Bound
UE	User Equipment
UMTS	Universal Mobile Telecommunication Systems
UP	User Preferences
USA	User Software Assistant
UTRAN	Universal Terrestrial Radio Access Network
VHO	Vertical Handover
VoIP	Voice over IP
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide interoperability Microwave Access
WINNER	Wireless World Initiative New Radio
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network

WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network
WWRF	Wireless World Research Forum

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Chapter 1

Introduction

1.1 Overview

The Heterogeneous Wireless Network (HWN) [1,2] integrates different wireless networks such as IEEE 802.15 WPAN [3,4], IEEE 802.11 WLAN [4,5,6], IEEE 802.16 WMAN [7], [8], Global System for Mobile communications (GSM) [9,10] Universal Mobile Telecommunications System (UMTS) [9], Digital Video Broadcasting (DVB) [11], and satellite networks [12] into one common network. The integrated networks often overlap coverage in the same wireless service areas, leading to the availability of a great variety of innovative services based on user demands in a cost-efficient manner.

Most of the modern wireless terminals have multiple radio interfaces for different wireless networks. This type of terminals is called multimode terminals [13]. The user with multimode terminal can roam among HWN with seamless mobility and service continuity. Modern multi-mode terminals are Software Defined Radio (SDR) based [14,15]. The SDR technology enables a wireless terminal to support various kinds of wireless systems and services by reconfiguring the terminal [16], so users can enjoy various wireless services in a seamless manner.

The current Radio Resource Management (RRM) [17,18,19] solutions and mechanisms for the wireless networks consider only the case of a single Radio Access Technology (RAT) where mobile users can only access that RAT and co-existing sub-networks can only be operated independently. The needs for supporting various applications and services and for providing ubiquitous coverage in the HWN require more complex and intelligent RRM techniques that enable the co-ordination among the different RATs.

Common RRM (CRRM) [20,21,22,23] and Joint RRM (JRRM) [16], [24,25,26] are two types of the processes that enable the management within a single and between the different RATs of the HWN. CRRM is a cooperative RRM architecture proposed by 3GPP [20,21] to make UMTS and GSM/GPRS networks cooperate. It is responsible for coordinating the individual RRM entities of each RAT. JRRM is another cooperative RRM architecture and mechanism proposed by IST TRUST [25] and SCOUT [26] projects and is similar to CRRM, but it is not restricted to GSM and UMTS. It also complements the CRRM with additional features and algorithms. Both JRRM and CRRM imply the use of some new RRM mechanisms such as Access Network Selection (ANS), Joint Admission Control (JAC), Joint Congestion Control (JCC), Joint Scheduling Control (JSC), and Vertical Handover (VHO).

The thesis concentrates on the first mechanism (i.e. ANS), which decides how to select the most suitable Access Network (AN) based on the discovered accesses, Quality of Services (QoS) constraints, operator policies, user preferences and available system capacity and utilization. In our work, a generic framework to solve the selection problems that utilizes the advantages and strengths of the parallel fuzzy logic decision making, the multiple criteria decision making and the genetic algorithms is presented. Based on the developed framework, several novel ANS algorithms have been designed, implemented, simulated and evaluated. Figure 1.1 shows the scope of our research inside the HWN area.

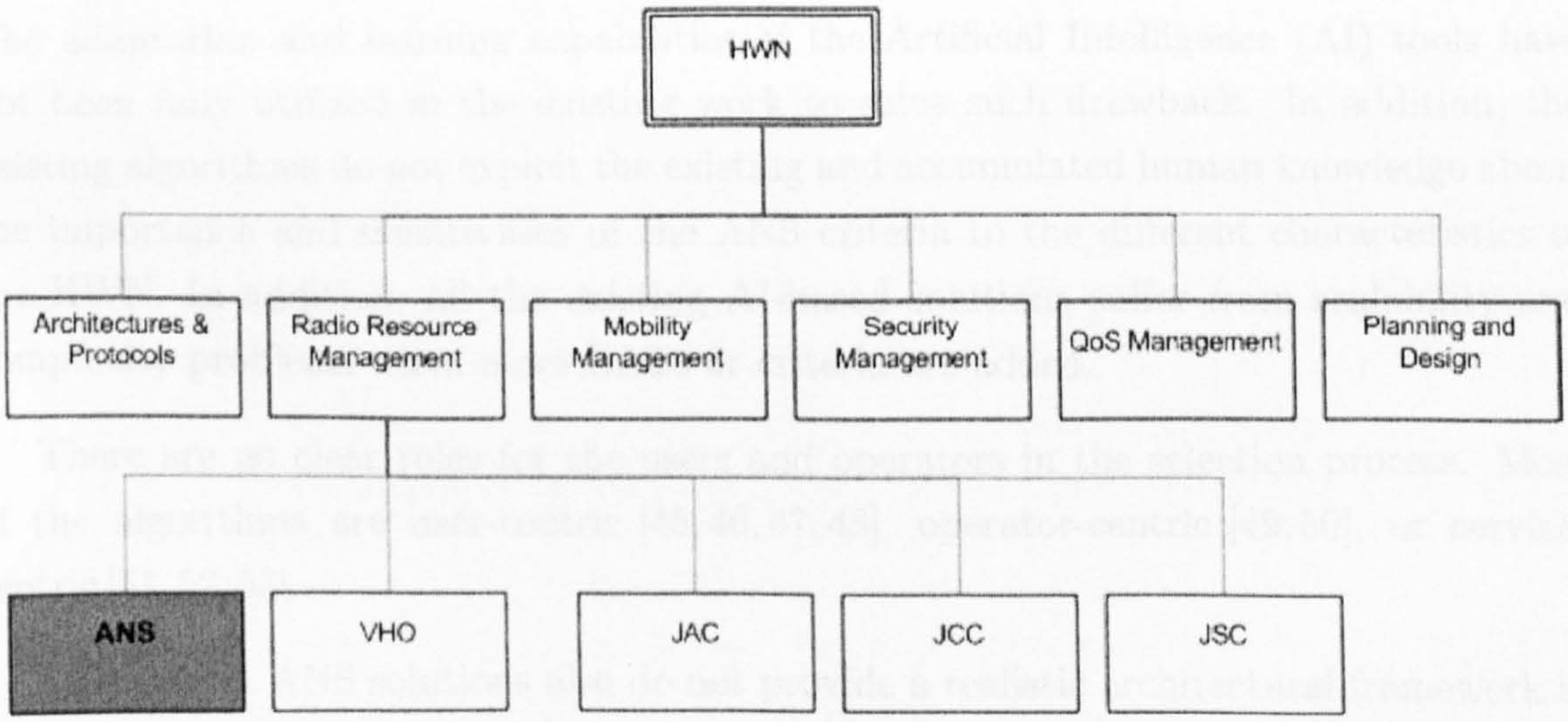

Figure 1.1: The research scope

1.2 The Motivations

Although ANS is one of the key components that must be addressed and considered carefully in the HWN environments, not many algorithms for the ANS problem can be encountered in the literature so far.

Most of the existing ANS algorithms [27,28,29,30,31,32,33,35,36,37,39,40,42,43,44] do not exploit the advantages of the multi-criteria nature of the access network selection that can give better performance than single criterion algorithms due to the flexible and complementary nature of the different criteria. Considering only one or two criteria in the ANS solution is not sufficient to provide a good solution and usually leads to undesirable situations. For example, if the solution is based only on the received signal strength criterion, this can easily lead to congested RATs, many unsatisfied users, inefficient utilization for the WWAN links, and many other undesirable situations.

The existed multi-criteria algorithms do not address the ANS as a multi objective problem where the operators, the users, the RATs conditions, and the applications have their own viewpoints regarding the ANS problem and every party wants to control the selection process. Each party has its own metrics to measure the efficiency and performance of the ANS solutions.

They also do not have proper methods to assign the weights of the different criteria. The adaptation and learning capabilities of the Artificial Intelligence (AI) tools have not been fully utilized in the existing work to solve such drawback. In addition, the existing algorithms do not exploit the existing and accumulated human knowledge about the importance and sensitivities of the ANS criteria to the different characteristics of the HWN. In addition, all the existing AI-based solutions suffer from scalability and complexity problems when more RATs or criteria are added.

There are no clear roles for the users and operators in the selection process. Most of the algorithms are user-centric [45,46,47,48], operator-centric [49,50], or service-centric [51,52,53].

The current ANS solutions also do not provide a realistic architectural framework in which the selection mechanism can work. The described use case scenarios are limited and not realistic from the perspective of deployment or the expected architecture for HWN and do not consider the relationship between the different collaborative or competitive operators involved in one HWN. As a result, they do not provide complete and deployable solutions to the selection problem.

Furthermore, some of the current algorithms could not distinguish between the initial ANS process (i.e. our thesis subject) initiated for the new service requests and the selection process during the VHO process. The two processes have obvious differences in the criteria and the performance evaluation metrics. Some other solutions do not distinguish between the ANS and JAC, where JAC usually goes one further step and allocates the required resources of the new coming or handoff services in the RAT selected by the ANS algorithm.

Even though the problem of network selection across HWNs has recently received much attention because of a drive for converged communication systems, to our knowledge no complete and comprehensive survey that summarizes the state of the art in the area of access network selection has been done so far.

1.3 The Objectives

The main aims of the investigation are to develop a new class of intelligent, scalable, and flexible ANS algorithms that maximize the user satisfaction and the operator benefit while improving the efficiency of the user services by providing better quality and resources utilization over the heterogeneous wireless environments. These aims are fulfilled by achieving the following objectives.

- Analyzing the ANS mechanisms and their functionality and specifying the main requirements, complexity and desirable features of the ANS solutions.
- Formalizing a generic framework that is able to decompose the ANS solutions into sub-layers and determine the tools applied to the solution. Practically, the framework utilizes the advantages of the application of the Fuzzy Logic (FL), Multi Criteria Decision Making (MCDM), and Genetic Algorithms (GA) to the ANS problem.
- Establishing realistic roles for the users and operators that consider the characteristics and type of the HWN and help to give complete and deployable solutions to the ANS problem.
- Developing and implementing a set of new algorithms based on the generic framework that consider the different viewpoints and distinguish between the initial

ANS and the VHO selection.

- Demonstrating and simulating the developed algorithms by means of simulation experiments.

- Evaluating the developed algorithms and demonstrating their potential in improving user satisfaction, operator benefits, and QoS.

1.4 Contributions of the Research

To provide the best possible solution to the ANS problem, the thesis makes the following contributions to the knowledge:

1. Development of a new class of ANS generic algorithms that are based on parallel FL based decision and MCDM systems. This class of algorithms represents the first attempt to develop adaptive, flexible, and scalable ANS algorithms that utilize the advantages of hybrid parallel FL decision making systems and MCDM systems.

2. Development of a new class of ANS generic algorithms that are based on parallel fuzzy logic based decision, MCDM systems, and GA. To our knowledge, no utilization for GA abilities for ANS has been carried out so far. Furthermore, we do not find any usage for the optimization and search tools that help to find suitable criteria weights for all the existing MCDM based ANS solutions.

3. Designing, implementing, simulating, and evaluating four novel and intelligent operator ANS algorithms. Two algorithms are developed for co-existing WLAN and WWAN networks and the other two algorithms are developed for co-existing WWAN, WMAN, and WLAN. All algorithms outperform several reference algorithms in terms of operator benefits, user satisfaction and QoS.

4. Development of a basic simulation test-bed for the performance evaluation of the ANS algorithms in the HWN. Our developed simulation environment and models for ANS algorithms performance analysis provide a significant foundation for more advanced and generic simulation test-bed for the CRRM mechanisms in the co-existing RATs of HWN.

5. Conducting a comprehensive experimental study for the effect of the different GA parameters and operators on the GA performance when dynamic components and variables dependency are existed in the fitness function.

6. Presenting new and fair roles for the operators and users in the access network selection process and identifying the effect of coupling level between the RATs in the access network selection process. To the best of our knowledge, these two issues have not been touched carefully in the previous work. In addition, thorough study of the ANS related aspects is presented, where a comprehensive foundation for ANS related issues is created mostly from scratch. To the best of our knowledge, no complete and comprehensive survey that summarizes the state of the art in the area of ANS has been done so far.

1.5 The Research Methodology

The adopted research approach consists of five main steps. The research study was initiated with a theoretical literature review. This review was conducted for the identification of a specific research problem. It also served the purpose of identifying potential, new, and novel solutions for the identified problem. The focus was in understanding CRRM mechanisms on the HWN and more specifically the ANS mechanism. A comprehensive and extensive study for the previous related works to identify their drawbacks and limitations and consequently determining the exact objectives, aims and expected contributions of our work was carried out. This step was conducted continuously and in parallel with the other steps throughout the period of this research. This was necessary to ensure that potential developments in related areas could be continuously fed back to the other activities throughout the research period.

In the second step, the ANS solutions blueprints in the different coupling scenarios of the HWN were presented. After that, the different cases that could trigger the ANS module or the VHO module were presented. The details of our conceptual intelligent framework to solve the optimized selection problems were described and the strengths and advantages of the developed framework were identified.

In the third step, four novel ANS algorithms that are based on the framework developed in the second step were implemented using the Matlab FL and GA toolboxes with a suitable Matlab code. Extensive experimental study were carried out to find suitable parameters' settings and to choose suitable operators for the GAs. Based on these experiments, the most attractive parameters and operators for our developed objective functions were suggested.

The next step was to carry out the simulation and performance evolution. This step started with the building of the simulation environment and models. This consists of building the system, mobility, propagation, services and traffic models. Then, a set of new performance evaluation metrics were identified for the ANS algorithms. Three different reference algorithms were identified, simulated and evaluated. Their performance was compared against our developed ANS algorithms performance.

In the last step, findings were documented and reported. In addition, a number of potential extensions for this study were also identified for future research and development. Note that, in practice, this process is inherently iterative.

1.6 The Thesis Outline

This thesis is organized into eight chapters. The following paragraphs present the outlines of the remaining chapters of this thesis.
Chapter 2: presents a comprehensive description for the most relevant aspects of the ANS problem and a brief description for the different AI tools that are utilized in this study to solve the ANS problem. The chapter starts with a brief overview about the HWN characteristics, features, coupling levels, and multi-mode terminals. In the next section the main JRRM and CRRM mechanisms (i.e. JAC, JCC, VHO, and JSC) in the HWN are introduced. The main aspects of the ANS problem including the ANS phases, desirable features, complexities, general requirements, and criteria are introduced in the third section. Intensive study for the related work is discussed in the forth section. In addition, the chapter gives a brief introduction to the AI related tools that are used in this research (i.e. FL, GA, and MCDM). In particular, the main concepts of FL, GA, and MCDM are explained in the fifth section.
Chapter 3: provides a comprehensive analysis for the ANS problem. It discusses the roles of the operators and users in the ANS process and suggests new roles for both of them. The different cases and scenarios that could trigger the ANS module or the VHO module are presented. The details of the proposed intelligent framework to solve the optimized selection problems are described. At the end of the chapter, the strengths of the proposed framework are discussed.
Chapter 4: presents a novel ANS algorithm based on the generic framework developed on chapter 3 that contains only the first and the second components of the framework with MCDM weights that are assigned manually. The developed algorithm works on an HWN that contains co-existed WWAN and WLAN networks and use parallel FL and

Simple Multi-Attribute Rating Technique (SMART) MCDM method. The components of the algorithm are described in detail.
Chapter 5: presents a novel ANS algorithm based on the generic framework presented on chapter 3 that works on an HWN that contains a co-existed WWAN, WMAN, and WLAN networks and uses the Analytic Hierarchy Process (AHP) MCDM method. Suitable structures for the FL decision based systems and the AHP MCDM component are proposed.
Chapter 6: presents the usage of the GA to optimize the weights of the SMART and AHP MCDM tools used in the ANS algorithms that are developed in chapters 4 and 5. This chapter carries out a big number of tests to determine good GA parameters and operators settings for the developed objective functions. Based on the conducted tests, the most suitable population size, crossover fraction, mutation rate, and elitism account for our application are suggested and the best selection, crossover, and mutation operators are specified.
Chapter 7: builds out the different simulation models that are used in this research. Practically, the system, mobility, propagation, services and traffic models are described. A new set of performance metrics and a set of reference algorithms are suggested in this chapter. Then, the chapter simulates and evaluates the developed algorithms in the previous chapters using the developed simulation models. The results achieved by the developed algorithms are compared with the achieved results by the reference algorithms.
Chapter 8: discusses the significant conclusions of our research and proposes several major areas and new directions of future research.

Chapter 2

Foundation of ANS Problem and AI Tools

Even though the problem of network selection across the Next Generation Wireless Network (NGWN) has recently received much attention because of a drive for converged communication systems, to our knowledge no complete and comprehensive survey that summarizes the state of the art in the area of ANS has been done so far. This chapter presents a comprehensive description for the most relevant aspects of the ANS problem and the different AI tools that are utilized in this study to solve the ANS problem. The chapter starts with a brief overview about the characteristics and features of the Next Generation Wireless Network (NGWN) and Multi-Mode Terminals (MMT). In the second section, the main JRRM and CRRM mechanisms in the NGWN and the different types of RRM and JRRM coupling levels are introduced. The ANS phases, desirable features, complexities, general requirements, criteria, and related work are discussed in the following section. After that, the chapter gives a brief introduction to the AI related tools that are utilized in this research (i.e. FL, GA, and MCDM). In particular, the main concepts of FL, GA, and MCDM are explained.

2.1 Next Generation Wireless Networks

A brief theoretical background about the NGWN (also called HWN, 4G, or B3G) related aspects are presented in this section. It is worthy to state that the terms {NGWN and HWN} and {CRRM and JRRM} are used interchangeably in this study.

2.1.1 NGWN Characteristics and Features

Different NGWN definitions can be found in the literature so far [54, 55]. Always Best Connected (ABC) paradigm [56, 57] defines the NGWN from the user perspective. In this paradigm, NGWN is defined as a new type of wireless networks where anyone can communicate with anyone else, anywhere and anytime, or enjoy any service of any network operator, through any network of any service provider in the most efficient and optimal way according to the user criteria.

The leading Japanese mobile communication operator, DoCoMo, introduces the concept of Mobile multimedia; Anytime, anywhere, anyone; Global mobility support; Integrated wireless solution; and Customized personal service (MAGIC) for the vision of NGWN [58]. This definition treats NGWN as the extension of 3G cellular service. Also, the European Commission (EC) definition for the NGWN focuses on ensuring seamless service provisioning across multi wireless systems and networks and providing optimum service delivery via the most efficient network available [59, 60, 61].

The following points extend the above perspectives and summarize the main expected features and characteristics of the NGWN.

- NGWN will combine a diversified and multi Radio Access Technologies (RATs) (e.g. WWAN, WLAN, WMAN, WPAN networks) to be integrated into one common network.
- NGWN will be all-digital and all-IP communication based with complete support for end-to-end QoS guarantees.
- NGWN will provide a large set of quickly deployable user services (i.e. anytime, anywhere and from any device) in a cost-effective manner under one billing mechanism.
- NGWN will support huge multimedia traffic (from several tens of megabits per second to 100 Mbps for outdoor and up to 1Gbps for indoor environments).
- NGWN will guarantee seamless and transparent user roaming with full support for various vertical handovers.
- NGWN will integrate the navigation and communication systems in order to offer a variety of location/situation/context aware services. It will support more advanced mechanisms for resources and mobility management.

- NGWN will support increased user personalization that enables the user to configure the operational mode of his/her device and pre-select the content of the services according to his/her preferences.

From the perspective of our study (i.e. the RRM perspective), the NGWN environments are defined as a very complex environments that need a new set of RRM mechanisms that work under very high complexity and uncertainty and utilize the advantages of the complementary characteristics of the different RATs to achieve anywhere, anytime services and bring benefits to both end users and operators.

2.1.2 Multi-Mode Terminals

According to [13], the multi-mode User Equipment (UE) is a terminal with at least one UMTS radio access mode (FDD and/or TDD) and it supports one or more other 2G RATs (e.g. GSM, cdmaOne, GPRS, etc.). On the contrary, the single-mode terminals are those terminals that support only one type of RAT. Moreover, [13] defines several types of UEs, namely Type 1 through Type 4. Type 1 of UE operates in each of the supported RATs as a single mode terminal and in one mode the UE does not scan for or monitor any other RAT. The change into another RAT is based on a manual selection. Type 2 of UE can perform monitoring and reporting of another RAT, while utilizing and working under another RAT. However, Type 2 does not have the capabilities to support simultaneous reception or transmission through the respective RATs. In addition to the capabilities of Type 2, Type 3 of UE can receive simultaneously from more than one RAT, but not transmit simultaneously in more than one RAT. However, to utilize these additional capabilities, a more complex UE structure has to be considered due to the cross impact of the two receptions. Type 4 of UE can receive and transmit simultaneously from more than one RAT. Utilization of the additional capabilities of the Type 4 UE compared to the Type 2 and Type 3 UE is considered too complex due to the cross impact of the two or more receptions and/or transmissions.

It is clear that, the categorization proposed by 3GPP assumes that there will be usually a cross impact of the multi receptions and/or transmissions of the different modes, which is true for voice communication services and not usually true for other type of services. For example, if a terminal with 3G and WLAN capabilities is considered, the 3G could be used for voice communication and the WLAN for Web browsing simultaneously without any considered cross impact. The considered multi mode terminal in our study is a terminal that could support more than one RAT, with at least one cellular RAN (e.g. 2G, 3G, etc.).

2.2 Radio Resource Management in NGWN

The current RRM solutions and mechanisms [17,18,19] for the wireless networks consider only the case of a single RAT where mobile users can only access that RAT and co-existing sub-networks can only be operated independently. NGWN will be composed of multiple RATs and domains, therefore new RRM schemes and mechanisms are necessary to benefit from the individual characteristics of each RAT and to exploit the gain resulting from jointly considering the whole set of the available radio resources in each RAT. These new RRM schemes have to support mobile users who can access more than one RAT alternatively or simultaneously using a multi-mode terminal. Common RRM (CRRM) [20,21,22,23] and Joint RRM (JRRM) [16,24,25,26] are two types of the processes that enable the management within a single and between the different RATs of the NGWN. CRRM is a cooperative RRM architecture proposed by 3GPP [20,21] to make UMTS and GSM/GPRS networks cooperate. It is responsible for coordinating the individual RRM entities of each RAT. JRRM is another cooperative RRM architecture and mechanism proposed by the IST TRUST and SCOUT projects [25,26] and is similar to CRRM, but it is not restricted to GSM and UMTS and complements the CRRM with additional features and algorithms.

The benefits provided by CRRM and JRRM are commonly agreed and fully described in [19,20,21,62,63]. The availability of multiple Radio Accesses (RAs) usually permits to do radio resource management in a more efficient way. For example, balancing traffic among different RAT, based on the radio cost and traffic load of each RAT, allows higher trunking gain [64]. In [65], the financial advantages of the multi-access networks are investigated and the results show that there is no significant cost in adding hot spots like subsystems (e.g. WLAN) to legacy cellular networks (e.g. UMTS). In such a hybrid network, dual-mode mobile equipment will access the service via a hot spot when inside the hot spot, or cellular system otherwise, which allows a better utilization for the high cost resources of the cellular system by increasing the usage of the low cost resources of the hot spot. Based on an analytical approach for a combined WCDMA and GSM/EDGE multi-radio access systems, I. Koo et al. in [66] highlight the amount and type of gain that is due to the aggregation of the system specific resource pools and the service-based assignment gain that is due to the assignment of services to systems where they are most efficiently handled. H. Liu et al. in [67] report a significant capacity increase (compared with a stand-alone UMTS system) when UMTS coverage is combined with WLAN hotspots. The capacity increase depends on the service type and percentage of WLAN coverage. [68] addresses the JRRM capacity gain. It shows that Joint Admission Control (JAC) algorithms for JRRM schemes can reach 60%-80% traffic gains when compared to the non-joint scheme. [22] shows that there is a capacity gain by sharing the resources from several overlapping layers/networks. The advantages of distributing the load among different networks to increase flexibility and reduce network equipment costs are addressed in [69]. Finally, L. Badia et al. [70] deal with the comparison between a non-cooperative and a cooperative approach between RATs and explore the possibilities of improvements achievable by allowing allocation on different RATs.

2.2.1 CRRM and JRRM Mechanisms

Both JRRM and CRRM imply the use of some new RRM mechanisms such as Access Network Selection (ANS), Joint Admission Control (JAC), Joint Congestion Control (JCC), Joint Scheduling Control (JSC), and Vertical Handover (VHO). The following paragraphs introduce a brief description about JAC, JCC, JSC, and VHO mechanisms. The ANS mechanism is introduced in section 2.3 in more comprehensive way.

Joint Admission Control (JAC)

JAC handles all new or handoff service requests in the NGWN. It checks whether the incoming service request to the selected RAT by the initial ANS or the VHO selection can be admitted. Then, it allocates the required resources and guarantees the QoS constraints for the service. The relationship between JAC and local admission controls of the involved RATs is highly dependent on the level of coupling and type of relationship between the CRRM entity and RRM entities of the coupled networks [71]. JAC algorithm, which considers the users preference in making an admission decision is proposed and a specific case where the user prefers to be served by the RAT which has the least service cost is modelled and evaluated by O. Falowo et al. in [72]. In [73] a JAC scheme for multimedia traffic that maximizes the overall network revenue with QoS constraints over coupled WLAN and CDMA cellular network is considered. Wang et al. [74] propose an adaptive call admission control for integrated cellular and WLAN network. In the proposed scheme, call admission decisions are based on requested QoS and availability of radio resources in the considered RATs. Karabudak et al. [75] propose a call admission control scheme for the heterogeneous network using genetic algorithm. The objectives of the scheme are to achieve maximum wireless network utilization and meet QoS requirements. A network capacity policy based joint admission controller is presented by K. Murray et al. [76], [77].

Joint Congestion Control (JCC)

With the information of estimated loads in all the coupled RATs, JCC (also called Joint Load Control (JLC)) is responsible for managing jointly (i.e. taking advantage of the JRRM concepts) the situation when one or more RAT load exceeds the pre-defined threshold(s). It ensures that the whole NGWN or any part of it is not overloaded and remains stable. When overload is encountered in one or more RATs, the JCC returns the congested RAT(s) quickly and controllably back to their targeted thresholds using new congestion resolution methodologies such as VHO. In [78], X. Gelabert et al. present a framework for JCC taking into account a scenario where CDMA and TDMA technologies were deployed. Some congestion resolution methodologies are presented taking advantage of the JRRM concepts. In particular, a congestion resolution method using VHO is presented and evaluated. This method proved to be suitable in scenarios where only one of the RATs is in a congestion state. In [79] the same authors extend their work and address the problem of congestion control in a scenario where the two available RATs (in particular, GSM/EDGE Radio Access Network and the UMTS Terrestrial Radio Access Network are considered) undergo simultaneous congestion situations. For this case, a congestion resolution scheme based on VHO jointly with a Bit-Rate Reduction (BRR) scheme is proposed and evaluated for a mixed services scenario considering voice and data users.

Joint Scheduling Control (JSC)

JSC is responsible for scheduling and splitting the traffic streams of a given user over multiple RATs (e.g. video stream with, basic layer and enhancement layer being transmitted over different RATs individually). It helps to optimize utilization of radio resources in the whole system. It also synchronizes the stream being split. [80] proposes schemes to control and distribute traffic over two different radio access networks, namely GPRS and

UMTS, with the aim of optimizing spectrum efficiency. K. Chebrolu et al. [81] address the access selection from users perspective and describe an approach to handle the jitters incurred by transmission on multiple interfaces. In [82], B. Xing et al. examine cases where an application is partitionable in flows of different demands, in terms of delay and bandwidth. They also consider the possibility of splitting this traffic in more than one path. In [83], the problem of multiuser scheduling with multi-radio access selection is addressed. That work assesses the performance gain due to multiuser diversity with respect to the single radio interface case, where users are constrained to connect to the same single radio access. In [84] a joint scheduling algorithm splitting traffic between a UMTS and HiperLan/2 systems is proposed. L. Qiang et al. in [85] address the significant and non-tolerated synchronizing delay that is caused by the independent scheduling of different RATs. Then, a JSC algorithm that can reduce synchronization delay in the case of a large amount of users by considering other RATs' scheduling situation is proposed. In [86] a joint scheduling mechanism allowing traffic to be split over a tightly coupled radio network is discussed.

Vertical Handover (VHO)

VHO is the common term given to handovers between the coupled access networks in the NGWN [87]. VHO (also called inter-system handover) is the capability to switch on-going connections from one Radio Access Network (RAN) to another. It enables users to access several networks such as WLAN, WMAN, WPAN, and WWAN in parallel. It allows the applications even the real time application to be seamlessly transferred among different networks. In order to achieve seamless vertical handover in heterogeneous network environments, it is necessary to guarantee service continuity and QoS, which means low latency and low packet loss during handover. [88] presents an FL based IP-centric vertical handoff decision algorithm and execution scheme between a WWAN and WLAN. In [89,90], a cost based function that effects the characteristics of different networks is used in the handover decision algorithms and a network elimination factor is introduced to exclude those networks that cannot meet the QoS constraints for specific services. Several VHO schemes are proposed in [91,92] trying to reduce the latency, packet loss and generally optimize the handover procedure.

2.2.2 Coupling Levels in NGWN

The term "coupling level" can refer to two different issues. In the one hand, it can refer to the extent of coordination and collaboration across different RATs involved in the NGWN and it indicates the type of relationship between CRRM entity and local RRM entities [93,94,95]. On the other hand, the term "coupling level", as used in 3GPP [96], mainly defines the reference point and interface in the network architecture where WLAN and 3G networks are connected. In our study, the first definition is used to define the functional collaboration between different RATs and the type of relationship between the CRRM entity and the local RRM entities. The following paragraphs summarize four possible coupling levels between RATs in the NGWN.

No Coupling

In this case, it is considered that, although different RATs operate in a heterogeneous scenario, there is not any collaborative RRM across the RATs and no specific functionalities are associated to the CRRM level. The local RRM entities are totally responsible for the management of the RRM resources of their RATs. Figure 2.1 shows this type of coupling level.

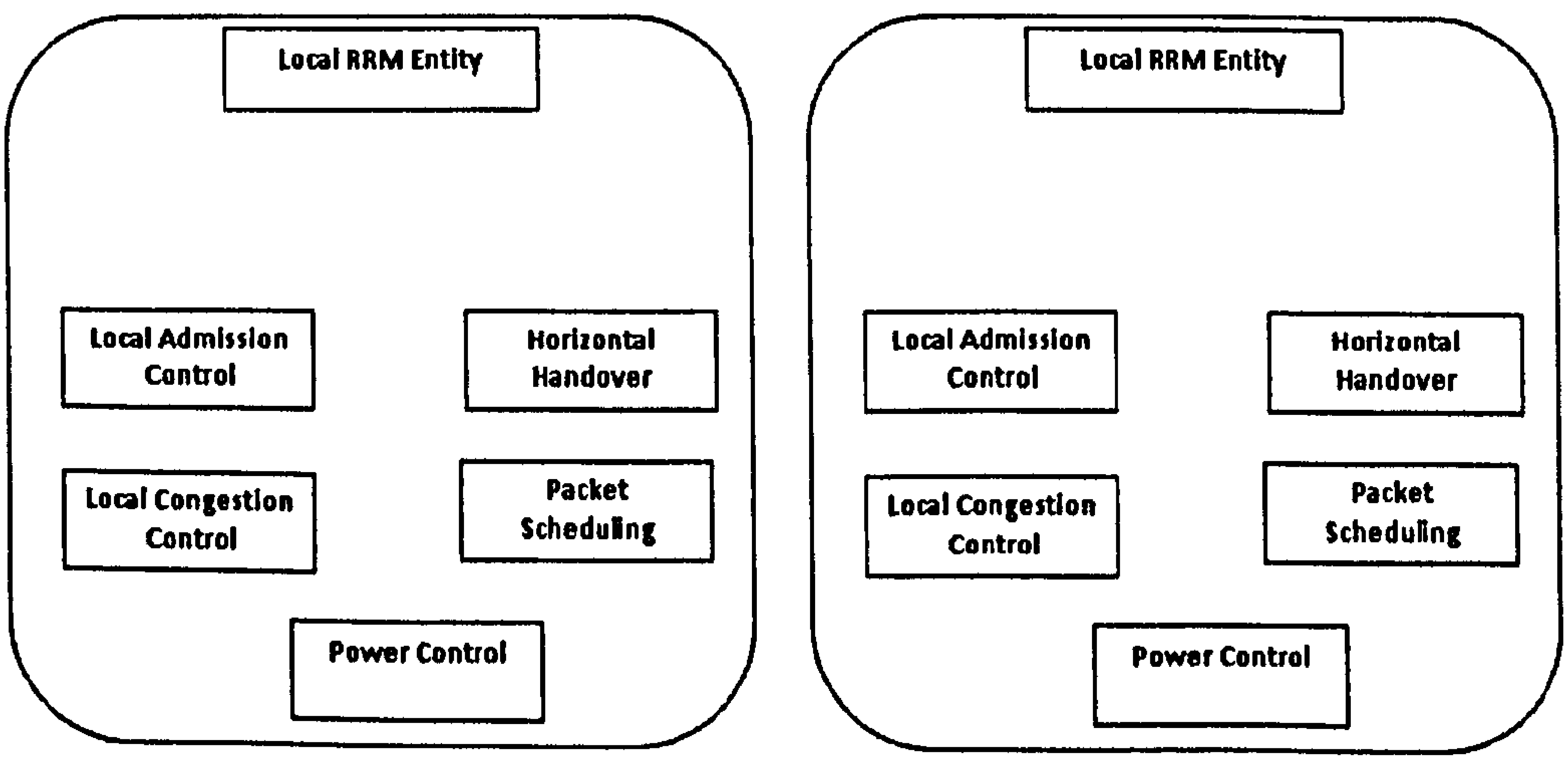

Figure 2.1: No coupling level

Loose Coupling

Collaborative RRM is performed across the RATs via a simple CRRM entity. The CRRM acts as a coordinator of the RAT-specific RRM functionalities. The CRRM entity is supplied with some measurements from the local RRM entities including the list of candidate cells for the different RATs and cell load measurements to perform CRRM mechanisms such as initial ANS or VHO. After the suitable network is selected, the local RRM entity of that network deals with the connection using local RRM mechanisms such as admission control, packet scheduling, congestion control, power control and horizontal handover. Figure 2.2 shows this type of coupling level.

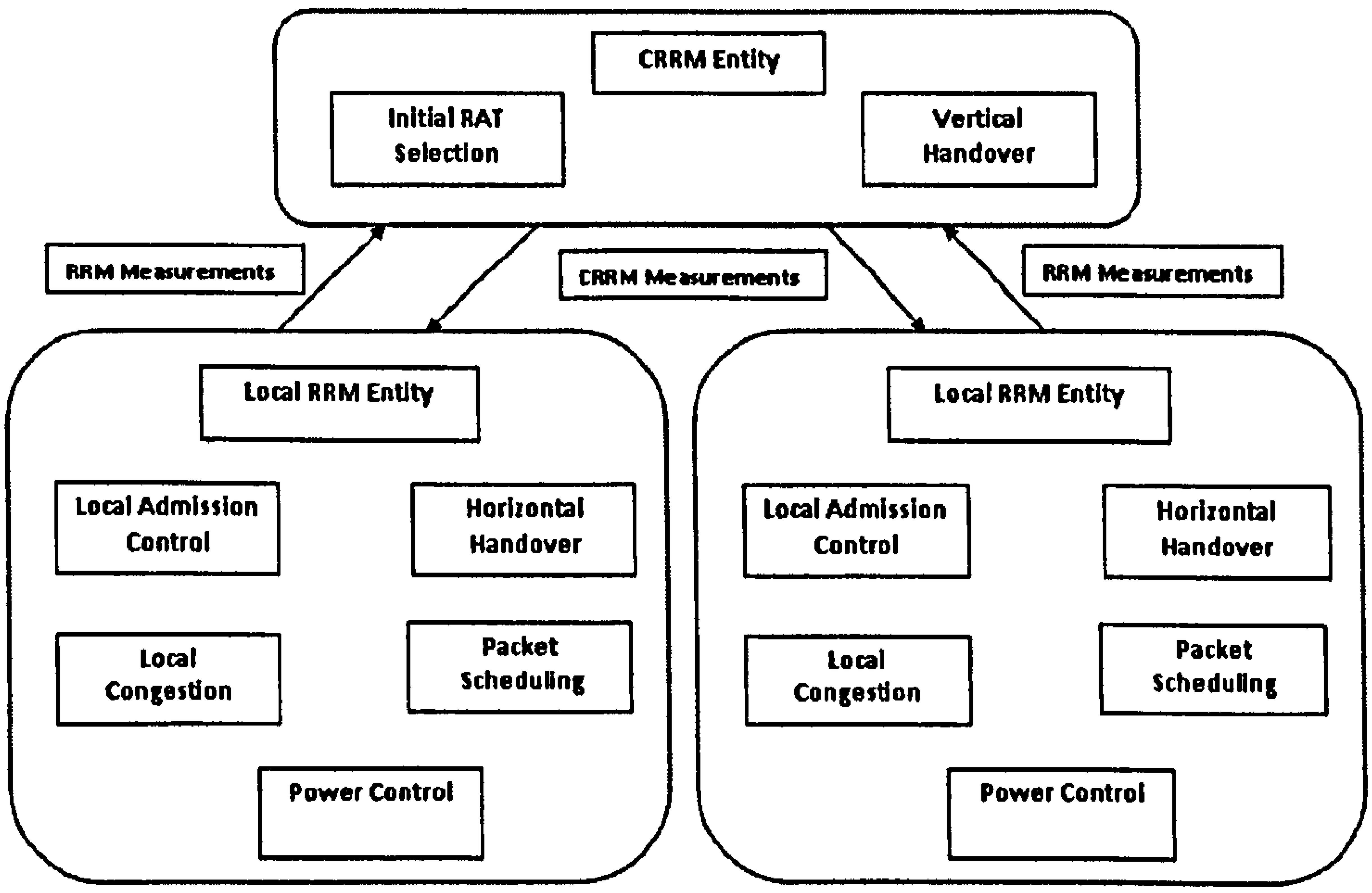

Figure 2.2: Loose coupling level

Tight Coupling

The CRRM acts as a coordinator of the RAT-specific RRM functionalities. This is achieved via interworking between the CRRM and the RAT-specific RRM entities. In this coupling level, some of the RRM functionality for the different RATs are integrated into the CRRM. For example, some local RRM mechanisms that operate on a long-term basis, like the admission and congestion control algorithms, can be moved into the CRRM level while keeping in the local RRM level the functions that operate at the radio frame level or below like the packet scheduling or the power control. Figure 2.3 shows this type of coupling level.

Very Tight Coupling

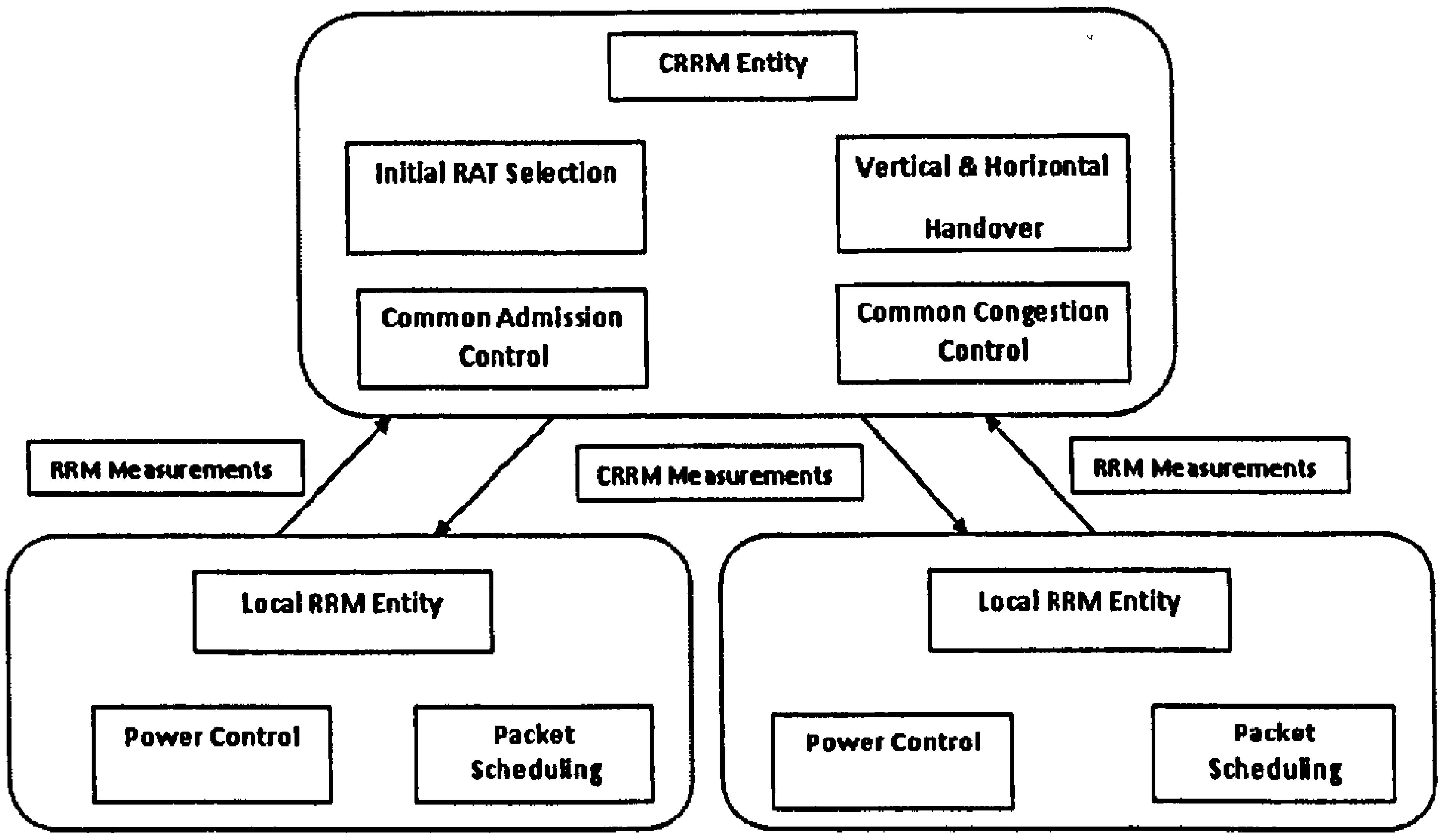

Figure 2.3: Tight coupling level

This level of coupling represents the highest degree of coordination between the different RATs. Collaborative radio resource management is performed across the RATs via a CRRM entity. The CRRM acts as a coordinator of the RAT-specific RRM functionalities. Once again, this is achieved via interworking between the CRRM and the RAT-specific RRM entities. In this coupling level, all RAT-specific RRM functionalities are integrated into the CRRM. Figure 2.4 shows this type of coupling level.

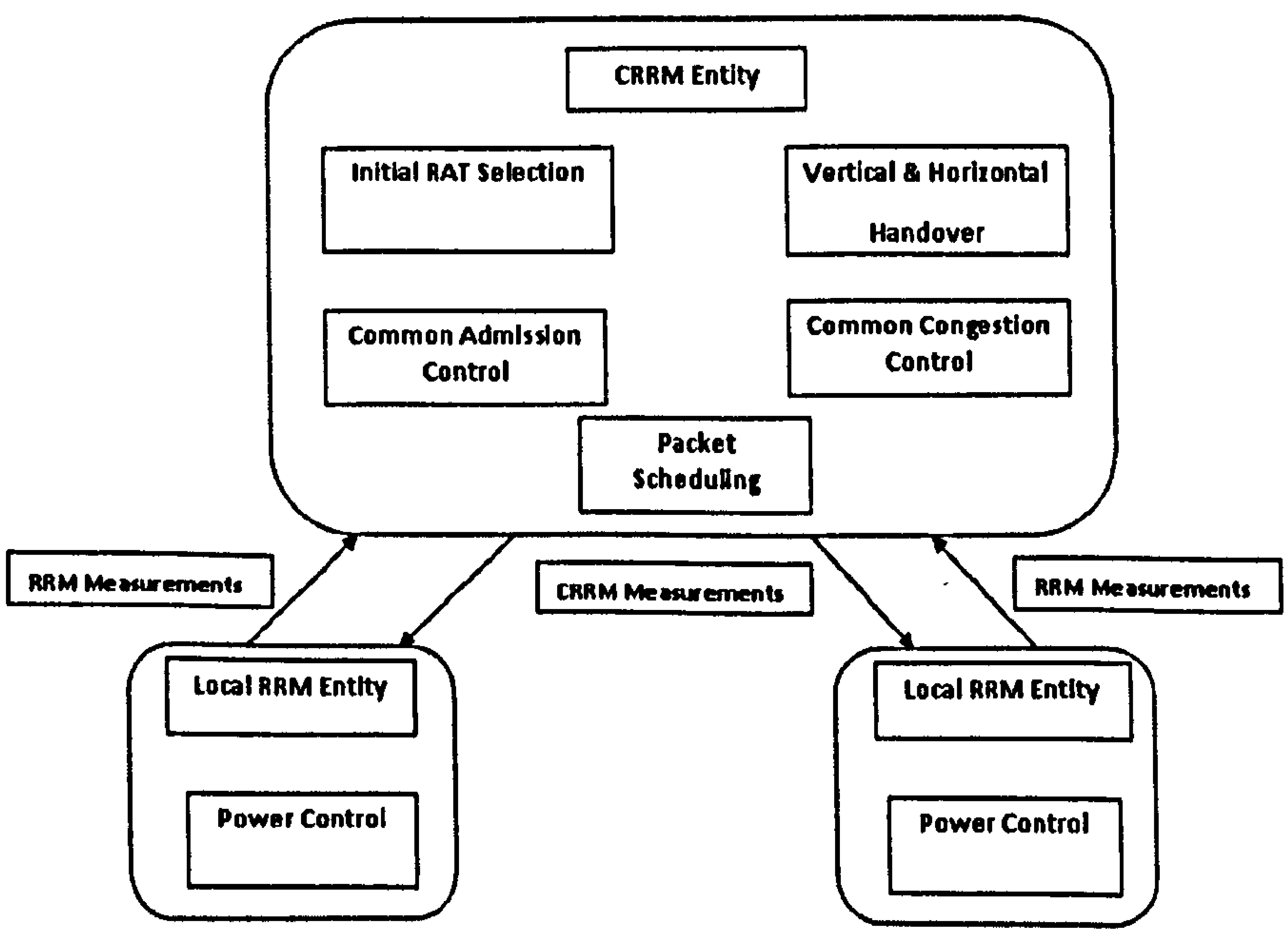

Figure 2.4: Very tight coupling level

2.3 Access Network Selection Problem

Access network selection is responsible for selecting the most optimal and promising AN for a new service request in the NGWN. This type of selection is also called the initial ANS to distinguish it from the ANS that happens when a VHO criterion is fulfilled. Another two reasons that initiate the ANS process are a) when the user changes his/her profile or b) when the availability of a new AN is detected. It is worth mentioning that the initial and vertical handover ANS are performed using different modules and algorithms. Our study concentrates on the initial ANS. In this thesis, the term "ANS" is used for initial ANS unless otherwise stated.

ANS is one of the key components that must be addressed and considered carefully in the NGWN environments. Selecting the most optimal and promising AN is an important consideration for overall networks stability, resource utilization, user satisfaction, and QoS provisioning. Choosing a non optimal network can result in problems such as the use of expensive access types or poor service experience. However, choosing the best RAT is not a trivial task and there are many parameters, criteria, and viewpoints to take into account when selecting the best AN. The ANS complexities, phases, desirable features, general requirements, and criteria are studied in this section.

2.3.1 ANS Complexities

There are several factors that complicate the ANS process and necessitate the design of better ANS algorithms. The following paragraphs summarize the complexities associated with the ANS process.

Multi-RAT Environments

NGWN will solicit the cooperation of heterogeneous Radio Access Networks (RANs) in order to enable the users to access information and services from anywhere, at any time over the coupled RATs in a very cost-effective manner from the users and operators perspectives. However, on the down side, the lack of uniformity in network characteristics (coverage, service capabilities and compatibilities, security, power consumption, bandwidth, delay, etc.) leads to very dissimilar, imprecise and contradictory data inputs for the ANS solutions.

Multi-Criteria Problem

The ANS is a multi-criteria problem in nature. This nature has to be utilized to provide a multi-criteria based solution that can give better performance than the single criterion based algorithms due to the flexible and complementary nature of the different criteria. Considering only one or two criteria in the ANS solution is not sufficient to provide a good solution and usually leads to undesirable situations. For example, if the solution is based only on the received signal strength criterion, this can easily lead to congested RATs, many unsatisfied users, inefficient utilization for the WWAN links, and many other undesirable situations.

Multi-Objectives Problem

The operators, the users, the RATs conditions, and the applications have their own viewpoints regarding the ANS problem and every party wants to control the selection process. Each party has its own metrics to measure the efficiency and performance of the ANS solutions. Any efficient solution has to resolve the complexity that arises from the conflict objectives of all parties and give each side a fair role in the selection process.

Multi-Operators Environments

The NGWN is a composition of multiple types of RATs that are owned by a single operator or multi-operators. The multi-operator could be collaborative or competitive. In each case, different sets and levels of roaming, billing, authorization and authentication agreements between the different operators have to be settled. Any complete ANS solution has to treat the complexity that arises from the NGWN multi-operator environment.

Complex Services

NGWN supports a wide variety of services that enable increased user personalization where the user is able to configure the operational mode of his/her device and preselect the content of the services according to his/her preferences. A variety of location/situation/context aware services that are not defined in 3G systems will appear due to the integration of the navigation and communication systems in the NGWN. These heterogeneous services have their own QoS constraints and requirements that add a new dimension of complexity that has to be treated by the ANS solution.

2.3.2 ANS Phases

The ANS procedure can be divided into three phases, the initiation phase, the decision phase, and the execution phase. In the initiation phase, the need for ANS is recognized and subsequently the ANS process is initiated. In the decision phase, a comparison of information and measurements from a variety of sources including networks measurements, QoS requirements, user preferences and operator policies is carried out. This comparison leads to the identification of the best available AN according to the defined performance evaluation metrics. The objective of the execution phase is to select the best AN in the initial ANS case or to change the cell, code, technology, mode, or AN in the VHO case according to the details resolved during the decision phase. Figure 2.5 shows the ANS procedure phases.

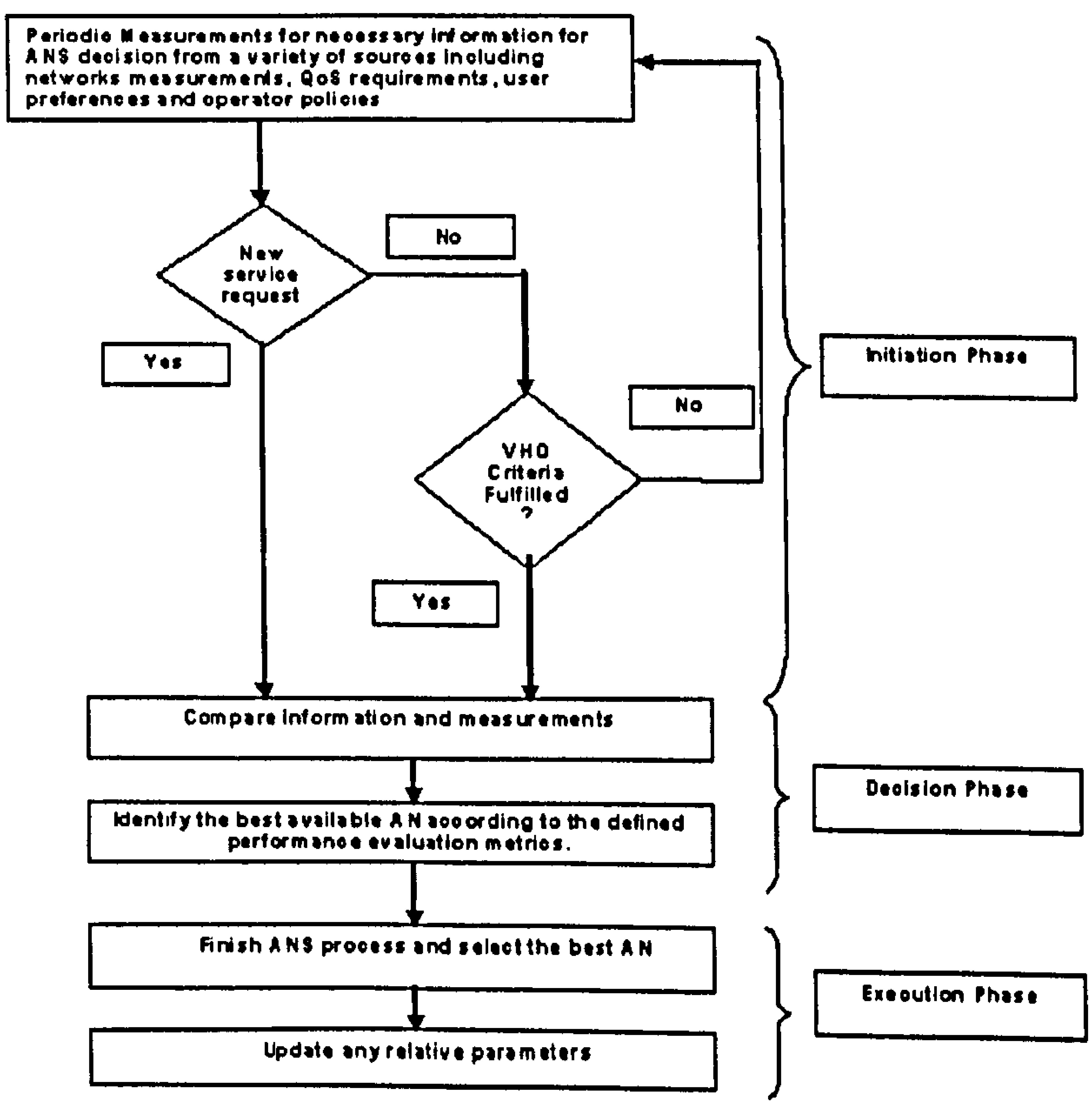

Figure 2.5: The ANS phases

2.3.3 ANS Criteria

To reflect the different viewpoints of the users, the operators, the QoS requirements and the networks conditions, different criteria can be applied to select the best network. The most important ANS criteria found in the literature so far can be categorized into operator criteria and user criteria.

The operator criteria reflect the operator policies. Usually these criteria are objective and quantitive criteria that are measured in the networks or retrieved from a pre-defined database. The most important operator criteria can be summarized as follows:

- **Received Signal Strength (RSS)**: it is usually better to connect the user to the network with the strongest received signal, because weak received signal can cause unnecessary handover, call drop, and packets or bits errors.
- **Mobile Station Speed (MSS)**: to avoid unnecessary handover overhead when moving from the ANs with small coverage area such as WPAN or WLAN to ANs with larger coverage area such as WMAN and WWAN, the low speed users are usually connected to the ANs with small coverage area and the high speed users are connected to the ANs with large coverage area.
- **Service Types and QoS Constraints**: due to the different QoS architectures and schemes used by the different networks, some networks such as WLAN are preferred for data, bursty services, and streaming multimedia services and other networks such as 3G networks are preferred for voice and conversational multimedia services.
- **Resource Availability (RA)**: to avoid any network congestion and to keep a balanced load between the co-existing networks, the new or handoff calls are usually connected to the network with higher available resources.
- **Signal to Interference Ratio (SIR)**: to guarantee better link quality and lower error rate, the network with the higher SIR has to be selected for the user.
- **User Preferred Price**: the operators assign the links of high cost networks (with better QoS) for users who are willing to pay more and the links of low cost networks to other users.
- **User Priorities**: the operators can set a priority for each user to reflect his/her Service Level Agreement (SLA) with the operator. For example, golden users

are assigned to the network with the best condition. Silver and bronze users are assigned to networks with worse conditions.

The user criteria reflect the user preferences. Usually these criteria are subjective and qualitative criteria. These criteria are not directly measurable, but a scale of degrees (levels) to measure each criterion can be used. The most important user criteria can be summarized as follows:

- **User Preferences (UP)**: the user may prefer to use one network more than the others due to the price, the type of service, or due to the degree of his/her previous satisfaction and experience.
- **Price**: the users may prefer to select one network among others due to its low price.
- **Terminal Type (TT)**: some terminal types such as laptops prefer to connect to specific networks such as WLAN. Other types of terminals such as PDAs prefer to connect to other networks such as WWAN.
- **Battery Status**: with a low power battery, the user may prefer the network that can save the power of the battery over the other available networks.
- **Service Type (ST)**: the users may prefer one network for specific type of services and prefer other networks for other types of services.
- **Subjective Network Reliability**: the users may prefer one network over the others because their previous experiences shows that this network offers more reliable service than the others.

2.3.4 Desirable Features for the ANS Solutions

In general, any ANS solution has to satisfy the following desirable features.

- The solution has to allow any type of inputs even the inputs with imprecise and dissimilar information and it has to be applicable to any type of ANs.
- The solution has to solve the ANS problem in a simple way with a low number of operations to ensure real time processing and to give a reasonable and acceptable delay before the decision appears.

- The solution has to react to the changing environment conditions and the accumulated human knowledge about the problem.
- The solution has to be scalable. The solution has to handle the increasing number of RATs and it also has to be able to handle a large number of criteria with a controlled complexity.
- The solution has to be complete and deployable in the environment where the selection mechanism can work.
- The solution has to cope with the different viewpoints and goals of the operators and users and to give both parties the right and fair roles in the selection process.
- The solution has to keep the required signalling overhead as low as possible.

2.4 Related Work

The problem of network selection across heterogeneous wireless networks has recently received much attention because of a drive for converged communication systems. The ANS solutions can be categorized into several categories in different dimensions based on different categorization criteria. Based on the number of decision criteria, the ANS solutions can be categorized into single-criterion based and multi-criteria based solutions. The ANS solutions can be categorized based on their orientation into user-centric, operator-centric, and services-centric solutions. The user-centric solution takes into account the user needs and satisfaction degree from the selection process. The operator-centric solution reflects the operator needs and benefits from the selection process and takes into account the network conditions. The service-centric solution reflects the QoS constrains and requirements of the different service types.

The ANS solutions can be categorized based on the centralization of the decision making as centralized, distributed (i.e. decentralized), and hybrid solutions. In the centralized mode (also called network-controlled mode), one CRRM entity controls the ANS decision or both the CRRM and local RRM entities control the selection process. In the decentralized mode (also called terminal-controlled mode), the ANS decision is controlled by the user equipment. In the hybrid solutions the decision process is either done by the terminal with the network assistance (called network assisted terminal-controlled mode) or done by the network with the assistance of the terminals (called terminal assisted network-controlled mode). In the hybrid solutions, some measurements are provided by one side to the other side to make the final processing of the ANS.

Based on the used problem solving method, the ANS solutions can be categorized into conventional (traditional methods based) and intelligent (AI methods based) solutions. The AI based solutions are much preferable in a very complex, changeable and uncertain environment such as the NGWN.

2.4.1 Single-Criterion based ANS Solutions

In the context of the single-criterion based ANS solutions, Y. Gwon et al. suggest different signal thresholds for each AN. The mobile terminal compares the RSS with the signal thresholds and decides the vertical handoff procedure [27]. M. Ylianttila et al. in [28] propose that the mobile nodes maintain connection with the higher throughput network until RSS goes below a threshold. Service types are considered and differentiating service is achieved by different levels of RSS [29]. In [30] a simple RAT selection for the WLAN and WWAN scheme where the user is sent to the WWAN for real time services and to WLAN for non real time services is proposed. In [31] user throughput based ANS algorithm is proposed, where the mobile station selects the network with the highest per user throughput. A network selection algorithm that is based on the distinct features of voice and data traffic is proposed in [32]. In this algorithm, the new calls prefer the cellular network for voice services and WLAN for the data services. Access selection mechanisms that determine which access network is best suited for a given application traffic flow is proposed in [33]. [34] proposes and evaluates a set of single criterion based access selection for data services in multi-access WCDMA-WLAN networks. In [35] M. Liu et al. propose a network selection for VHO based on an RSS estimation algorithm. In [36] Zahran et al. propose an adaptive VHO decision algorithm in which the application specific signal strength threshold is introduced. In [37] that relates to an UMTS-WLAN environment, the VHO decision is based on both RSS and distance criterion. J. Hultell et al. in [38] investigate two different strategies; one in which users connect to nearest AP and one more advanced strategy where the users select an AP so that the average user bit rate is maximized. Integrated heterogeneous networks by a UMTS network and one WLAN hotspot are studied in [39], where the voice services blocked by UMTS are converted into Voice over IP (VoIP) and directed to WLAN, while data services are served by WLAN if inside the coverage, otherwise by UMTS. A general framework for a policy-based RAT selection with some specific examples are proposed by P. Romero et al. [40]. A selection decision based on the service type criterion is used in [41]. More access selection for VHO algorithms that use RSS as the basic criterion can be found on [42] and [43]. In [44] a utility-based access selection algorithm targeted to achieve load balancing between UMTS and WLAN networks is developed. The utility functions are constructed so that each networks capacity is considered to achieve the load balancing.

In general, the current conventional single criteria based algorithms such as those proposed in [27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44] are rigid and take only one criterion, which is not sufficient to make a network selection in heterogeneous networks. This type of algorithms cannot react easily to the changing environment conditions and the accumulated human knowledge. Usually they cannot cope with the different viewpoints and goals of the operators, users, and QoS requirements, which make them inefficient for a multi criteria problem such as ANS problem. In addition, single criteria based algorithms are usually designed for specific types of networks, because the single criterion that is important for one type of networks may not be so important for other types of networks, for example the interference parameter in CDMA based networks is much more important than in TDMA based networks.

2.4.2 Multi-Criteria based ANS Solutions

The ANS decision deals with making a selection among a limited number of candidate networks from various service providers and technologies with respect to different criteria. Hence, it is a typical multi criteria decision making problem and it is more practical to apply multi-criteria based solutions to such a problem. Multi-criteria based solutions can be further categorized into user-centric, operator-centric, and services-centric solutions or into network-controlled, terminal-controlled, and hybrid solutions as described in the following paragraphs.

User-Centric, Operator-Centric, and Services-Centric ANS Solutions

A number of multi-criteria user-centric network selection algorithms have been proposed in the literature. A dynamic user-centric network selection decision which optimizes VHO selection across heterogeneous networks is proposed in [45]. The proposed network selection utilizes user-defined policies and cross-layer information including physical, link and application layer. Venom et al. [46] propose a user-centric selection approach that estimates user satisfaction regarding the selection of radio links in heterogeneous wireless networks. A simple user-centric VHO selection system across heterogeneous wireless networks is presented in [47], which allows users to express policies on what is the best wireless system at any moment. A policy-based VHO selection mechanism for mobile multi-homed hosts is presented in [48] by Ylitalo et al. The selection decision is based on explicit user defined policies and considers different criteria in the order of user defined priority.

The proposed user-centric schemes allow the users to access any preferred networks on the assumption that users' requests are all accepted and maintained by the preferred networks. This is much suitable for loose or non-coupled HWN. However, this assumption is not realistic in tight-coupled HWN since network operators have their own policies and could reject or terminate a less-valuable call in order to accept or maintain another more-valuable call. As a result, the user-centric network selection schemes apply users preferences to networks, but fail to guarantee complete success in assigning the user to the selected networks. The user centric solutions ignore the benefits of the operator that have to be considered. They also do not consider the accounting, roaming, and authorization agreements between the different operators who are sharing the ownership of one NGWN, which have considerable effect on the acceptance of user selection.

A number of operator-centric access selection algorithms have been proposed in the literature. The operator-centric soultions are usually a network-controlled or terminal-assisted network-controlled solutions. However, a network-controlled solution is not usually operator centric. In [49], G. Koundourakis et al. introduce a network-controlled approach for access selection in the context of resource management in heterogeneous wireless environments of co-existed UMTS, WLAN and DVB-T. The proposed approach focuses on the optimization of the resources, while ensuring acceptable QoS provision to the end users. H. Jia et al. in [50] propose a low complexity, centralized network-controlled selection scheme, aiming to optimally distribute the end users to the networks of the heterogeneous wireless system to maximize the global spectrum efficiency.

The operator centric solutions care about the operator benefits and ignore or underestimate the user preference, which is unacceptable on the NGWN that is based on the service personalization concept. In the pure network-controlled approach, the operators keep tight control over users to achieve the most beneficial utilization of their spectrum. In this selection mode, the client makes no measurements. This mode results in intensive network signalling and wasted radio resources and leads into high latency and long decision times. The centralized structure of the network-controlled mode means limitations in scalability and flexibility since the network entities can only handle up to a certain amount of traffic. However, we usually can say that the centralized mode is more efficient in terms of the availability of global information and can easily overcome any limitation on the user terminal. The network-controlled mode can be enhanced with the assistance of the user terminal. In the mobile-assisted network controlled mode, the network entity decides on the selection based on the measurement result from the mobile terminal.

Some service centric solutions can be founded in the literature so far. [51] describes the adaptation of ELimination and Choice Translating REality (ELECTRE) MCDM tool for ranking the network alternatives during the network selection process. The network selection is depending upon the QoS requirements of the service being requested by the user device. In [89], several optimizations are proposed for the execution of vertical handoff decision algorithms, with the goal of maximizing the QoS experienced by each user. [52] applies Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) MCDM tool to the problem of network selection. The algorithm depends upon the QoS requirements of the service being requested by the user device. J. Noonan et al. in [53] examine the ANS decision and propose that it is made by the client application while considering the RATs characteristics and costs. The criteria used in the QoS centric are not sufficient to guarantee the user satisfaction or to maximize the operator benefit.

A few solutions consider the different viewpoints for the operators, the users, and/or the QoS constraints. In [97] A. Iera et al. present a multi-criteria network selection algorithm that relies on a suitably defined cost function, which takes into account metrics reflecting both network related and user preference related objectives. In [83] R. Veronesi et al. propose two ANS strategies: a network-controlled strategy where each RAT chooses the user to schedule at each time, based on channel conditions and the requested QoS, and a terminal-controlled strategy, where each terminal chooses the preferred RAT, based on RAT capacity and channel condition. A network selection scheme, which decides an optimum network through discovering a trade-off among users preferences, operators benefits, network conditions and application requirements, is developed in [98]. [99] proposes a net utility-based network selection algorithm, where a utility function is used to reflect the user satisfaction level to QoS and a cost function is used to reflect the cost for service. Q. Song and A. Jamalipour [100, 101] propose the combined application of two mathematical techniques in an algorithm for network selection between UMTS and WLAN, where the Analytic Hierarchy Process (AHP) and the Grey system theory are used to evaluate the users preferences and service requirements, and combine the priority settings of the QoS attributes with the performances of the network alternatives to make the network selection decision. [63] builds a database that consists of user/service preferences and technical parameters, to make the selections decision. In [102, 103], an ANS algorithm for combined HSDPA and WLAN systems is investigated. Terminal type, traffic specification, user preference and mobile speed are used as selection criteria.

Terminal Controlled ANS Solutions

The user-centric solution is usually a terminal-controlled or a network-assisted terminal-controlled solution either explicitly or implicitly. An explicit terminal-controlled solution, which focuses on utility functions that describe the user preferences is introduced in [104]. A comprehensive terminal based decision making process to rank candidate networks for service delivery to the terminal is described in [105]. In [106] the implementation of decentralized RAT selection strategies at the mobile terminal in a HWN is addressed. A specific RAT selection strategy for co-existing CDMA/TDMA networks that aims to reduce interference by allocating users according to the measured path loss is analyzed. In [107] Q. Nguyen-Vuong et al. propose an effective terminal-controlled and user-centric network selection policy that gives the users the freedom to select the best access network that maximize their satisfaction degree. A terminal-controlled network selection scheme for NGWN, where a price mechanism guides the users to select the most efficient network and controls the allocation of network resources is proposed by H. Chan et al. in [108].

The main idea behind the terminal-controlled selection is to utilize the growing capabilities and computational power of current mobile terminals, to remove some of the management overhead from the network equipments and to distribute it to the powerful terminals. Moreover, the mobile terminal is in a strong position to make selection decisions since it has access to the information and measurements relating to its capacity, user preferences and user profiles and it has the knowledge of neighbouring access networks. Accordingly, the terminal will be able to select the most efficient access network in terms of user satisfaction and preferences and perform the ANS in a scalable and flexible manner. However, terminal-controlled ANS is claimed to be inefficient in doing the selection based on the operators policies and benefits, because of the limited information available at the terminal side to make such a decision (e.g. the terminal does not know what the cell load is). Nevertheless, this can be avoided if the network is able to provide some information or guidelines to the terminal assisting its decisions. In the network-assisted mobile-controlled mechanism, the network assists the terminal in the selection process by performing data collection and analysis to provide the network ranking. Again, the pure mobile-controlled solution is mainly a user-centric solution which still suffer from the shortcomings of the user-centric mechanisms stated above.

AI based ANS Solutions

All the above mentioned conventional multi criteria based algorithms do not take into account the complexities and uncertainties that arise from the different characteristics and natures of the different RATs. For these algorithms, it is not an easy task to incorporate the accumulated human knowledge about the problem and the only method to adapt the algorithms is to change the criteria weights randomly to get better results. In addition, these algorithms have not a proper method to assign the weights of the different criteria. To overcome these potential drawbacks in the conventional multi criteria based algorithms, several AI based ANs are proposed. CRRM strategies based on reinforcement learning mechanisms that control fuzzy-neural joint admission control and bit rate allocation algorithms to ensure certain QoS constraints are presented by L. Giupponi et al. and R. Agusti et al. [109, 110, 111]. The same authors extend their algorithms to VHO for real time services in [112]. A. Wilson et al. [113] propose a decision strategy for optimal choice of wireless access network using FL as the inference mechanism. A selection algorithm based on the fuzzy multiple objective decision making system is presented by P. Chan et al. [114].

The above algorithms do not address the effects of the user and operator roles on the selection decision making. They do not consider the trade-off between the criteria of the ANS problem and do not specify the importance and sensitivity of each criterion to the selection problem. The current intelligent multi criteria based algorithms suffer from scalability and modularity problems. Usually they cannot cope easily with the increased numbers of RATs and criteria in the NGWN. The intelligent multi criteria algorithms such as the proposed ones in [109, 110, 111, 112, 113, 114] take all inputs from the different RATs to one traditional fuzzy system, so they will suffer from scalability and complexity problems when more RATs or membership functions are added due to the expected huge number of complex inference rules.

2.4.3 Additional Shortcomings on Previous Work

In addition to the shortcomings that are pointed out separately for each solution and for the different types of algorithms in this section, all the above algorithms do not address clearly the roles of the users and the operators in the selection process. Also, all of the existed work does not find out the effects of the coupling level in the NGWN on the ANS solution. Furthermore, most of the current RAT selection algorithms could not distinguish between the initial selection process for the new service request and the selection decision during the VHO process. In addition, the previous work does not provide a realistic architectural framework in which the selection mechanism can work. The use case scenarios described are limited and not realistic from the perspective of deployment or the expected architecture for HWN and do not consider the relationship between the different collaborative or competitive operators involved in one HWN. As a result, they do not provide complete and deployable solutions to the selection problem.

2.5 The AI Tools

The main concepts of the utilized AI tools in this research (i.e. fuzzy logic, multiple criteria decision making, and genetic algorithms) are explained briefly in this section.

2.5.1 Foundation of Fuzzy Logic

Fuzzy Logic (FL) [115, 116] is a problem solving method based on the theory of fuzzy sets, where variables can have different degrees of membership in different sets. A universe of discourse is defined as the whole range of fuzzy sets to which a variable can belong. Each set on this universe is referred to as a membership function and is often described using a linguistic variable. On the universe of discourse, a variable has a degree of membership on each membership function that varies between 0 and 1. FL uses rules with antecedents and consequents to produce outputs from inputs. The antecedents are the inputs that are used in the decision-making or control process or the IF parts of the rules. The consequents are the implications of the rules or the THEN parts [117].

Fuzzy Logic Control (FLC) is based on the principles of FL. FLC is a non-linear control method, which attempts to apply the expert knowledge of an experienced user to the design of a controller. Figure 2.6 shows a typical fuzzy control system. The fuzzy control system contains four main parts, the fuzzifier, the fuzzy rules base, the fuzzy inference engine, and the defuzzifier. The fuzzifier maps the real valued numbers into a fuzzy set, which is the input to the fuzzy inference engine. The fuzzifiction process includes the definition of the universe of discourse and the specification of the linguistic variables, the fuzzy sets for the linguistic variables, and the membership functions for the specified fuzzy sets. The fuzzy rules base consists of a collection of fuzzy IF-THEN rules to represent the human knowledge about the problem. The fuzzy inference engine maps the input fuzzy sets into output fuzzy sets and handles the way in which the rules are combined just as humans use many different types of inferential procedures. The defuzzifier task is the reverse operation to the fuzzifier. It maps the output fuzzy sets into real valued numbers.

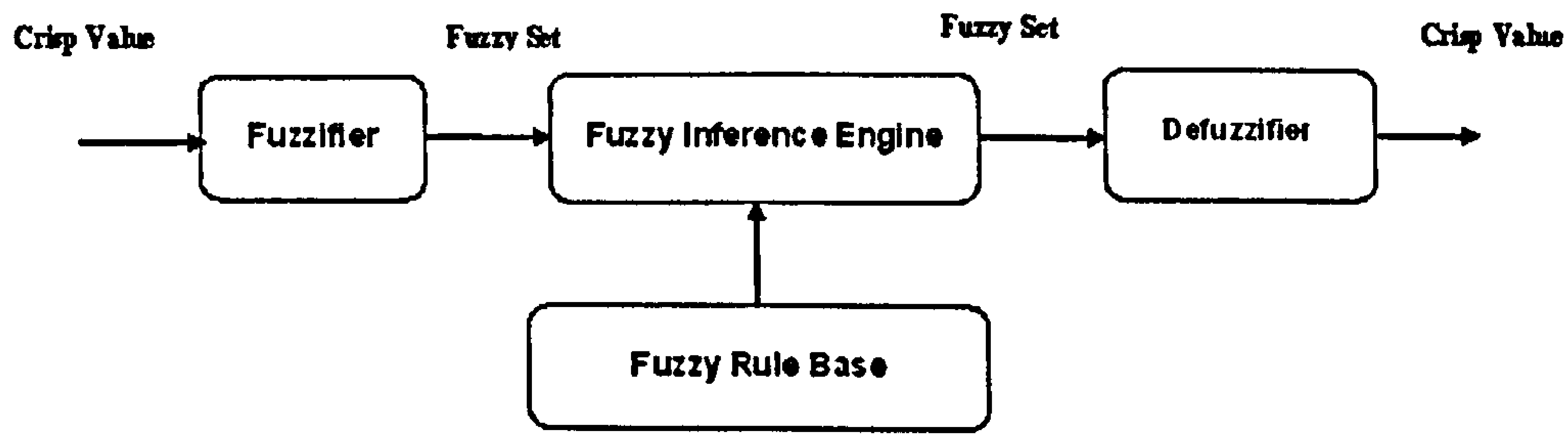

Figure 2.6: A typical FLC system

2.5.2 Foundation of Multi Criteria Decision Making (MCDM)

A good definition provided by Harris [118] for decision making as

> "Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision makers".

Making a decision implies the existence of different alternatives to be considered and the decision makers have to choose the alternative that best fits with their goals, objectives, and desires. Figure 2.7 shows an eight-step decision making process. The process flows from top to bottom can be described as follows [119, 120]:

Step 1: Define the problem: this step defines the multi-criteria issue in a clear problem statement that describes both the initial conditions and the desired conditions.

Step 2: Determine the requirements: this step defines the conditions and constraints (i.e. the requirements) that any acceptable solution to the problem must meet.

Step 3: Establish the goals: this step defines the objectives and the goals that have to be achieved by the solution.
Step 4: Identify the alternatives: alternatives offer different approaches to achieve the objectives subject to the defined constraints. The decision makers evaluate the constraints and goals defined in the previous two steps and suggest alternatives that meet the requirements and satisfy as many goals as possible.
Step 5: Define the criteria: this step defines the decision criteria that discriminate among the alternatives based on the goals. Usually no one alternative will be the best for all defined criteria, which necessitate the usage of the multi criteria.
Step 6: Select a decision making tool: the MCDM tool selection is highly dependent on the complexity of the considered problem and on the experience of the decision makers. Usually the decision maker starts using simpler tool and more complex analyses and tools can be added later if needed. Two important MCDM tools have been used in our study namely the Simple Multi-attribute Rating Technique (SMART) and the Analytic Hierarchy Process (AHP) method. The two methods can be described briefly as follows:

- **Simple Multi-attribute Rating Technique (SMART)** [121]: SMART is one of the simplest and most efficient MCDM methods. This method utilizes simple utility relationships. Each alternative A_j has a ranking value X_j that is obtained simply as the weighted algebraic mean of the utility values a_{ij} associated with it according to equation 2.1.

$$x_j = \frac{\sum_{i=1}^{m} w_i a_{ij}}{\sum_{i=1}^{m} w_i} j = 1, 2, ...n \tag{2.1}$$

- **The Analytic Hierarchy Process (AHP)** [122, 123, 124]: AHP is a well-organized MCDM method for representing the elements of any problem hierarchically. AHP is based on a set of pairwise comparisons between the alternatives on each of the decision criteria and a similar set of pairwise comparisons that are made to determine the relative importance of each criterion. At the end, the total weights for each alternative with respect to all criteria is produced. The pairwise comparisons are made using a nine-point scale, where 1 = equal importance or preference, 3 = moderate importance or preference of one over another, 5 = strong or essential importance or preference, 7 = very strong or demonstrated importance or preference, and 9 = extreme importance or preference.

Step 7: Evaluate the alternatives against the criteria: alternatives are evaluated using quantitative (i.e. objective) criteria, qualitative (i.e. subjective) criteria, or a combination of both types. The criteria are weighted and used to rank the alternatives.
Step 8: Validate the solutions against the problem statement: after the evaluation process selects a preferred alternative (or ranks the alternatives) in the previous step, the solution should be checked out to ensure that it truly solves the identified problem by fulfilling the desired conditions, meeting the requirements, and best achieving the goals of the decision makers.

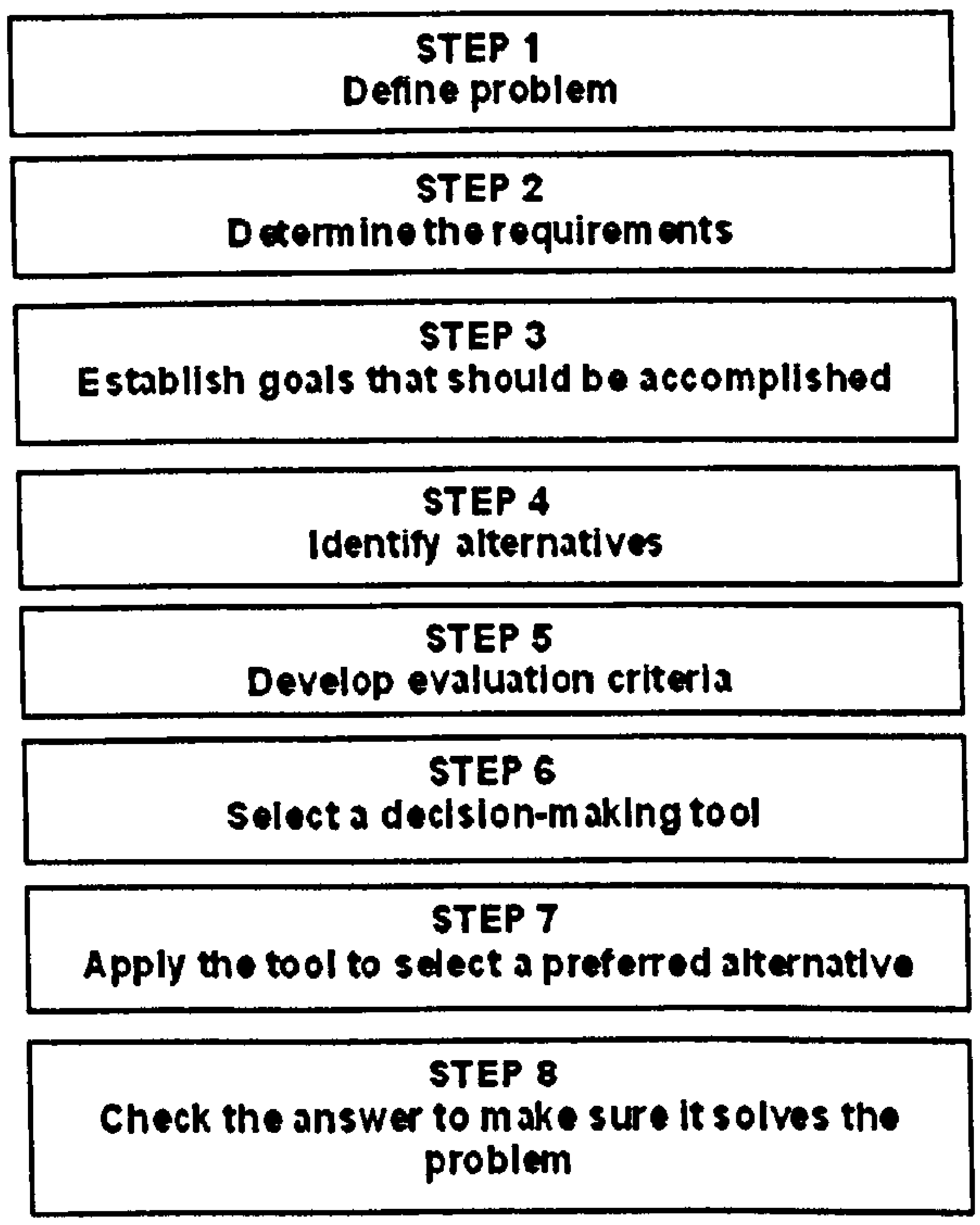

Figure 2.7: General decision making process

2.5.3 Foundation of Genetic Algorithms

Genetic algorithms (GA) [125, 126] are general purpose search algorithms that are based on the principles of the natural genetics theory to evolve solutions to a wide range of problems. According to this theory, in a population evolving in a particular environment, only the fittest individual is able to reproduce, while the less fit is exterminated, due to environmental constraints. The GA solving method is applied to problems that have no efficient solution with the aim of coming up with a good, but not necessarily optimal solution. The basic idea of GA is to maintain a population of chromosomes representing candidate solutions to the problem being solved, which evolves over time through a process of competition and controlled variation. A GA starts off with a population of randomly generated chromosomes, and advances toward better chromosomes by applying genetic operators modelled on the genetic processes occurring in nature. During the successive generations, chromosomes in the population are rated for their adaptation as solutions, and on the basis of these evaluations, a new population of chromosomes is formed using a selection mechanism and specific genetic operators such as crossover and mutation. An evaluation or fitness function must be identified for each problem to be solved. Given a particular chromosome (i.e. possible solution) the fitness function returns a single numerical fitness, which is supposed to be proportional to the utility or adaptation of the solution represented by that chromosome. The GA algorithm is stopped when it reaches to a satisfying result, when a predetermined number of generations have been created or when the time limit has been reached. The final solution is an individual with the best (i.e. maximum or minimum) value of fitness function. Figure 2.8 shows a block scheme of a basic GA. The main components of a typical GA are summarized in the following points.

- **Encoding:** in order to implement the GA algorithm, the set of parameters that give the best solution in optimization must be encoded into a suitable format so that crossover and mutation operations can be applied. Encoding depends heavily on the problem. The most famous encoding methods are real, integer, and bit string encoding methods.

- **Fitness Function (Objective Function):** the role of the fitness objective function is to represent the requirements to adapt to. It forms the basis for selection, and thereby it facilitates improvements.

- **Selection Function:** the parents of the next generation are selected based on their fitness function value. The function that performs the selection is called the selection function. Many selection functions are proposed so far such as stochastic uniform, remainder, roulette, and tournament selection functions. To ensure the survival of the best individual so far, elitism is used. Elitism is the process of selecting the better individuals of the previous generation and copying it to the new members of the population in the new generation. Elitism is important since it allows the solutions to improve over time. Besides, it helps to speed up convergence

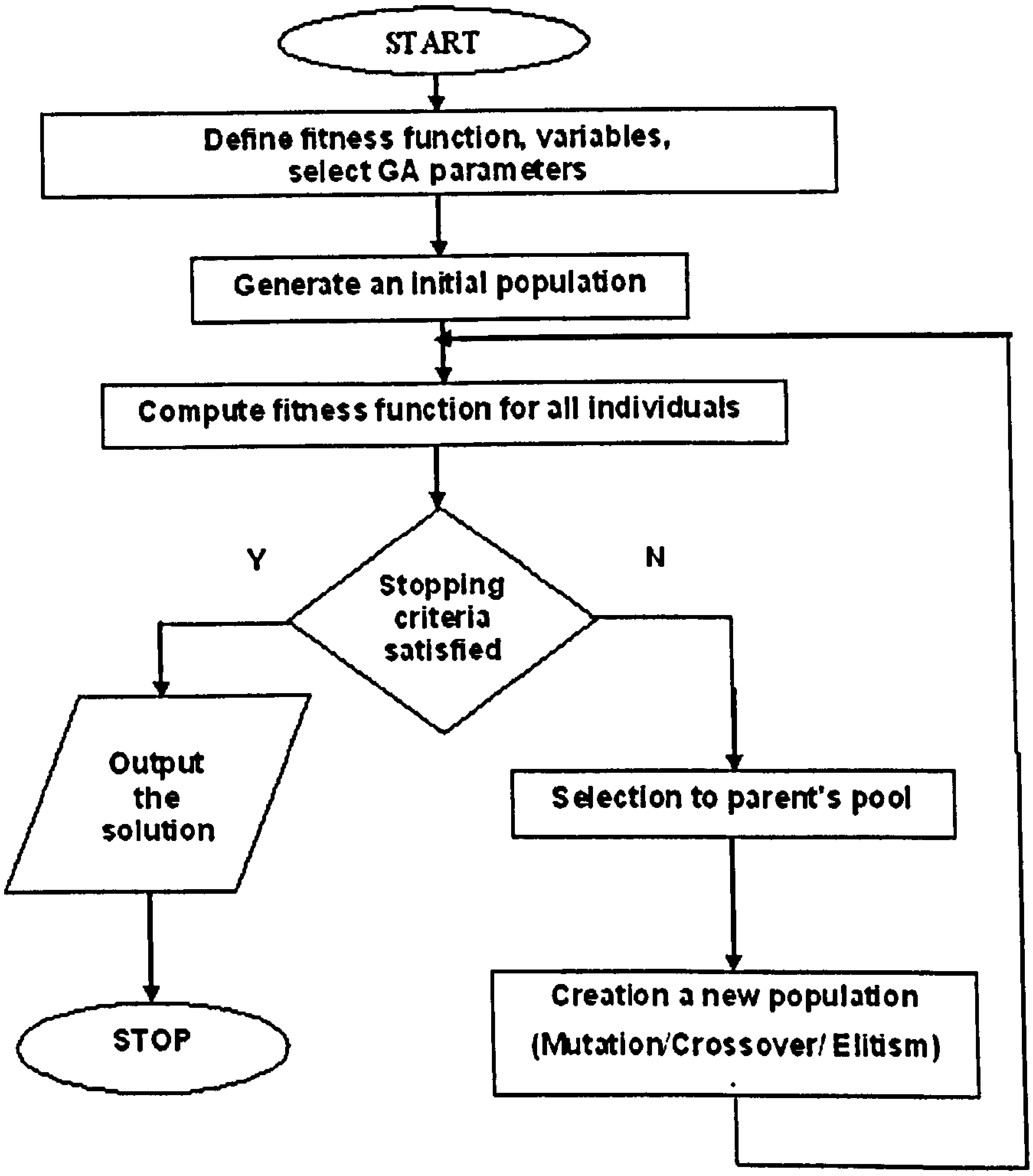

Figure 2.8: Typical GA components

of the GA.

- **Crossover Function**: crossover combines two individuals, or parents, to form a new individual, or child, for the next generation. The function that performs the crossover is the crossover function. Many crossover functions are proposed such as scattered, single point, two point, intermediate, heuristic, and arithmetic crossover functions.

- **Mutation Function**: to provide genetic diversity and to enable the GA to search a broader space, small random changes are made in the individuals in the population. These small changes are called mutations. The function that performs the mutation is called the mutation function. Different mutation functions are proposed so far such as uniform, Gaussian and adaptive feasible mutation functions.

- **Stopping criteria**: to determine what causes the algorithm to terminate, different stopping criteria can be used such as number of generations, time limit, fitness limit, stall generations and stall time limit.

2.6 Summary

Access network selection (ANS) is the radio resource mechanism that is responsible for selecting the most optimal and promising access network (AN) for a new service request in the Next Generation Wireless Network (NGWN). ANS is one of the key components that must be addressed and considered carefully in the RRM of the NGWN environments. Choosing a non optimal network can result in problems such as the use of expensive access types or poor service experience. However, choosing the best RAT is not a trivial task and there are many parameters, criteria, and viewpoints to take into account when selecting the best AN.

There are several factors that complicate the ANS process and necessitate the design of better ANS algorithms. The first factor is the lack of uniformity in RATs characteristics that leads to very dissimilar, imprecise and contradictory data inputs for the ANS algorithms. The second factor is the multi-criteria and multi-objective nature of the ANS problem, where several criteria and conflict objectives of operators and users have to be reconciled. Third factor is the complexities that arise from the NGWN multi-operator environment nature, where a different sets and levels of roaming, billing, authorization and authentication agreements between the different operators have to be settled and considered by the ANS solution. A forth factor is the new set of heterogeneous services that are not defined in 3G systems and that have their own QoS constraints and requirements. These new services add a new dimension of complexity that has to be treated by the ANS solution.

The current algorithms do not address the effects of the user and operator roles on the selection decision making. They do not consider the trade-off between criteria of the ANS problem and do not specify the importance and sensitivity of each criterion to the selection problem. The current intelligent multi-criteria based algorithms suffer from scalability and modularity problems. Usually they cannot cope easily with the increased numbers of RATs and criteria in the NGWN. The business scenarios described are limited and not realistic from the perspective of deployment or the expected architecture for HWN. In the next chapter a conceptual framework for the ANS solutions is developed.

The framework is based on parallel FL, MCDM and GA. In addition, the ANS process in the different scenarios in the NGWN is discussed extensively.

Chapter 3

ANS Scenarios, Cases and Solving Framework

The existed ANS algorithms do not address clear roles for the users and the operators in the selection process. The use case scenarios described are limited and not realistic from the perspective of deployment or the expected architecture for HWN and do not consider the relationship between the different collaborative or competitive operators involved in one HWN.

In addition, the adaptation and learning capabilities of the Artificial Intelligence (AI) tools have not been fully utilized in the existing work to exploit the accumulated human knowledge about the importance and sensitivities of the ANS criteria to the different characteristics of the HWN.

This chapter presents and discusses (a) The roles of the operators and users in the existed ANS solutions, (b) A new set of roles for both users and operators, (c) The ANS solution blueprints in the different coupling scenarios of the HWN, (d) The different cases that could trigger the ANS module, (e) The details of our developed intelligent framework to solve the optimized selection problems, and (f) The justifications and feasibility for the framework design.

3.1 User-Centric or Operator-Centric

For any ANS solution, the actors who are the responsible for the ANS procedure have to be addressed carefully. The operators, the users and the applications have their own viewpoints and objectives regarding the ANS process and each party want to control that process.

In fact, the roles of the operators and users have not been investigated clearly in the existing ANS solutions so far. *Who has the right to select the best access network is still an unsolved question, because there are many definitions for the word "best" and many definitions for the term "NGWN"*. It has been found that all the proposed works either give the total right of the selection to the users (i.e. user-centric solutions) or to the operators (i.e. operator-centric solutions). In both cases, this is unfair and unrealistic.

In the one hand, the NGWN allows the users to enjoy a wide range of high quality and low price services and applications by controlling the selection of the best network for them. On the other hand, the operators are expecting to gain more and more profits and benefits by saving their high cost networks resources by utilizing the resources of other low cost networks and by jointly considering the whole set of available radio resources in all RATs. Hence, both the users and operators need to share the rights of selecting the best ANs and apply their own definitions for the word *"best"*. A new set of operators and users roles that are based on the type and level of coupling between the networks involved in the NGWN are suggested on this chapter.

Another important issue that has to be considered is the difference between the initial ANS and the vertical handover selection. This difference affects the decision criteria and the performance metrics. The operators and users roles are also different in both VHO selection and initial ANS. Two different modules and solutions have to be considered, one for the initial ANS and another one for the vertical handover selection.

3.2 ANS in the Different NGWN Coupling Scenarios

This section discusses in details the ANS process in the different NGWN coupling scenarios and presents our suggested fair and new roles for both operators and users in the selection process.

3.2.1 Scenario I: A User with Multi-Mode Terminal in a Non-Coupled Multi-Operator NGWN

In this type of environments, each RAT works independently and no CRRM functionalities exist because no interconnection between RATs exists. In a non-coupled multi-operator environment, the user terminal is the only entity that is aware of the surrounding networks and the only one entity that is able and authorized to collect the required information from the different RATs. It is fair and more efficient to give the user the total right to control the selection. In addition, the user subscribes at these different networks owned by multi-competitive operators to get a better and wider range of services at a low price and he/she has the total right to make the selection decision. In this case, it is recommended to use a network-assisted terminal-controlled ANS algorithm that mainly depends on the user preferences and some networks measurements (to reflect the RATs conditions and characteristics). The ANS solution helps the user to select the best RAT according to his/her preferences.

It is worth mentioning that the considered type of NGWN in this subsection does not satisfy most of the characteristics of the NGWN, but nowadays this scenario is too common due to the existing commercial multi-mode terminals.

To illustrate this scenario, assume a user with a multi-mode terminal that could support GSM, UMTS, Wi-Fi, and WiMAX. With a new service request a menu with two options appears in the user terminal. The two options are the manual selection and the automated selection. If the user selects the manual selection option, a menu for the list of available RATs appears. If for example the UMTS network is selected, the request is sent to the local RRM entity of the UMTS network that takes the required actions to admit the user and allocate the resources. If the user selects the automated selection option, the network-assisted terminal-controlled algorithm that resides in the user terminal is activated. The selection algorithm selects the best network and sends the service request to the RRM entity of the selected network that takes the required actions to admit the user and allocate the resources.

3.2.2 Scenario II: A User with Multi-Mode Terminal in a Loose Coupled NGWN

In this type of environments, the ANs do not have anything in common, but the core networks are connected together using a public Internet Protocol (IP) based network. Collaborative radio resource management is performed across the RATs via a simple CRRM entity. The CRRM entity acts as a coordinator of the RAT-specific RRM functionalities, but without any integrated functionality for JAC, JSC or JCC. For VHO, loose coupled NGWN cannot support the service continuity to other AN without a very high delay and big packet loss. However, for initial ANS the case is a little bit different because it is mainly triggered due to a new service request, where more delay can be accepted.

Loose coupled environments can be categorized based on the ownership into three types. The first type is owned by multi-competitive operators. The second type is owned by multi-cooperative operators (i.e. there are billing, authorization and roaming agreements). The third type is owned by a single operator. For the first type, there are no agreements between the operators and the only place to make the selection decision is the user terminal, because it is the only entity that has (and is able to collect) the required information to make the decision. Hence, the solution for the first type should be similar to the solution in the first scenario and it is fair and more efficient to give the user the total right for the selection.

For the second and third types of the loose coupled NGWN, both the CRRM and user terminal entities have the abilities to make the decision because both entities have the abilities and authority to collect the required information. Hence, the ANS solution should contain two modules. The first module resides in the user terminal. It contains a network-assisted terminal-controlled algorithm to reflect the user viewpoint in the selection decision and it is the same as in the non-coupled environment. The second module resides in the CRRM entity. It contains a terminal-assisted network-controlled algorithm to reflect the operator viewpoint of the selection decision. The terminal-assisted network-controlled algorithm is mainly based on the operator policies and network conditions and it takes into account the user selection sent from the user terminal. All the used criteria values are collected from the local RRM entities and from the user terminal and sent to the CRRM entity. Hence, for the second and third types of NGWN, the selection rights are shared between the users and operators.

3.2.3 Scenario III: A User with Multi-Mode Terminal in a Tight or Very Tight Coupled Multi-Operator NGWN

In this type of environment, the different ANs are connected to one common core network through common interfaces using special interworking units and the ANs are connected to each other through a well defined interface. The CRRM entity acts as a coordinator of the RAT specific RRM functionalities, with some or full integrated functionality such as JAC, JSC, VHO or JCC. Our proposed ANS solution in this case is similar to the solution of the second and third type in scenario II. To illustrate this scenario, assume a user with a multi-mode terminal that could support GSM, UMTS, Wi-Fi, and WiMAX. With a new service request a menu with two options appears in the user terminal. The two options are the manual selection and the automated selection. If the user chooses the automated selection option, the network-assisted terminal-controlled algorithm, which resides in the user terminal is activated and ranks the available networks. If for example the networks are ranked as UMTS, WiMAX, GSM, Wi-Fi, the request is sent to the CRRM entity and activates the terminal-assisted network-controlled algorithm that takes the user selection into account and ranks the networks again, for example in the order UMTS, WiMAX, GSM, and Wi-Fi. Hence, the UMTS is selected as the best network for both user and operator and the local UMTS RRM entity is asked to take the required actions to admit the user and to allocate the resources.

3.2.4 The Whole Picture

This subsection tries to put everything together and give a brief summary about the proposed ANS solution. On the user side, the multi-mode terminal has a special module for the initial ANS that cares about the selection of RAT for a new service request and it is based on network-assisted terminal-controlled ANS algorithm. Another module is used for the VHO that cares about the selection of RATs when the VHO criterion is fulfilled.

On the operator side, if the CRRM entity exists (no CRRM entity in loose coupled multi-competitive operators and non-coupling levels), a special module for the initial ANS and another module for the VHO module are existed. The initial ANS module is based on an terminal-assisted network-controlled ANS algorithm.

Both algorithms (user and operator) have to interact with each other to select the best RAT. They also have to interact with the other modules for the rest of CRRM mechanisms such as the JAC and JSC. In addition, the operator algorithm has to interact with the local RRM of the selected network if it is still existed (no local RRM in very tight coupling). It is important to note that the initial ANS is not responsible for the allocation of the required resources for the services. The local admission control of the selected network or the JAC module is directly responsible for the resources allocation.

In any scenario the user can select the network using a special Software Assistant (SA) in his/her terminal based on the user algorithm. However, the affect of this selection depends on the type of NGWN environment. In a non-coupled multi-operator NGWN environment or in a none collaborative multi-operator loose coupled NGWN, the user selection controls the ANS. In a collaborative multi-operator loose coupled NGWN or in the tight/ very tight NGWN the user selection is sent to the initial ANS module on the CRRM entity. The user selection is considered as an important criterion of another selection SA on the operator CRRM. The operator SA is based on the operator ANS algorithm.

3.3 The ANS Cases

In each scenario, four main cases could happen. In the first case, the initial ANS module is triggered due to a new service request. In the second case, the VHO module is triggered when the VHO criteria is fulfilled. In the third case, the user changes his/her preferences. In the forth case, the availability of a new AN is detected by the user terminal. Figure 3.1 shows the possible ANS scenarios and cases and the following subsections describe in details the different cases.

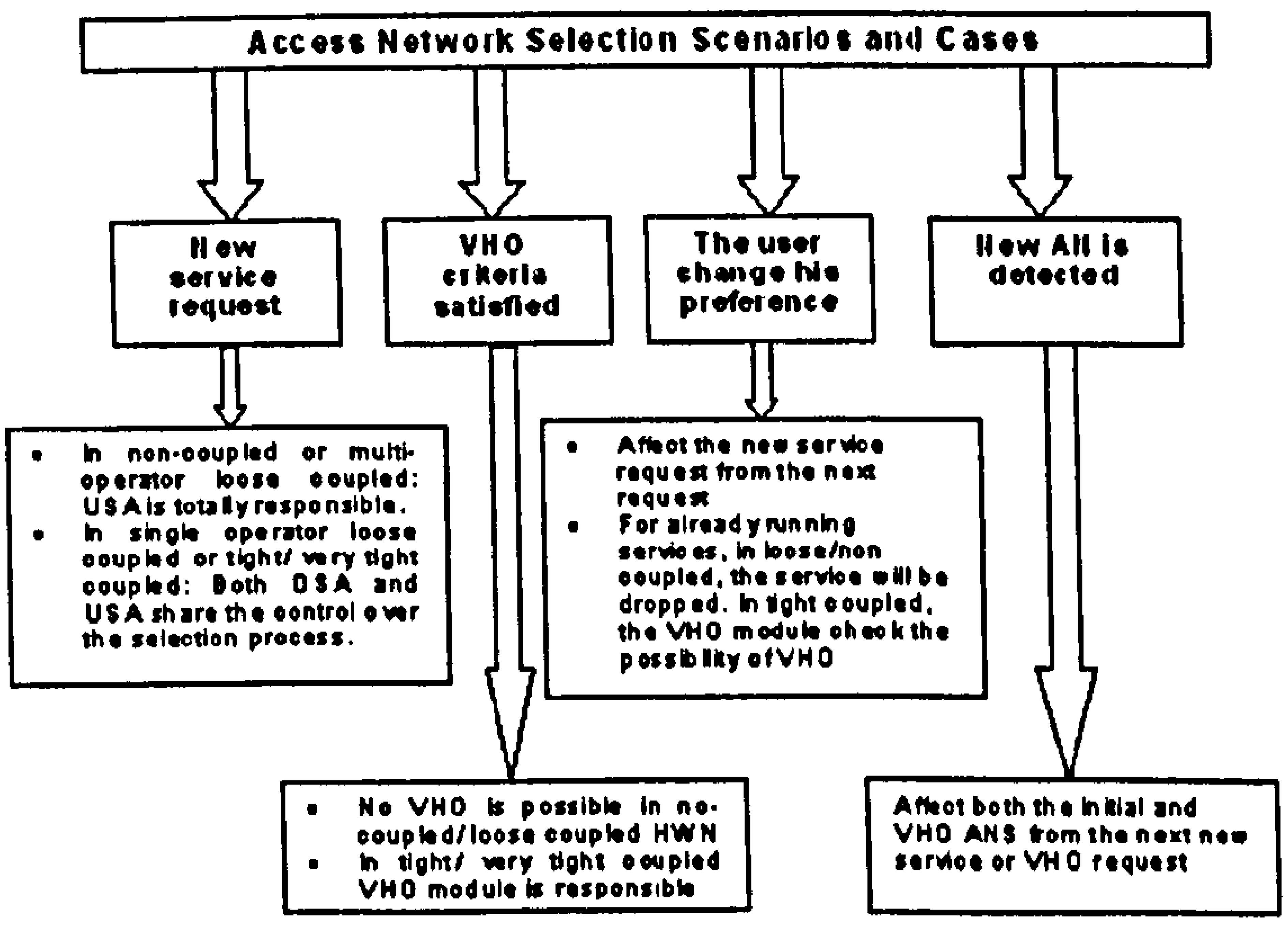

Figure 3.1: ANS scenarios and cases

3.3.1 Case 1 in Scenario I and Scenario II

In this case, a new service request in a non-coupled or multi-operator loose coupled environment NGWN triggers the initial ANS module in the user terminal. The main steps and interactions in this case can be shown in figure 3.2 and are explained as follows:

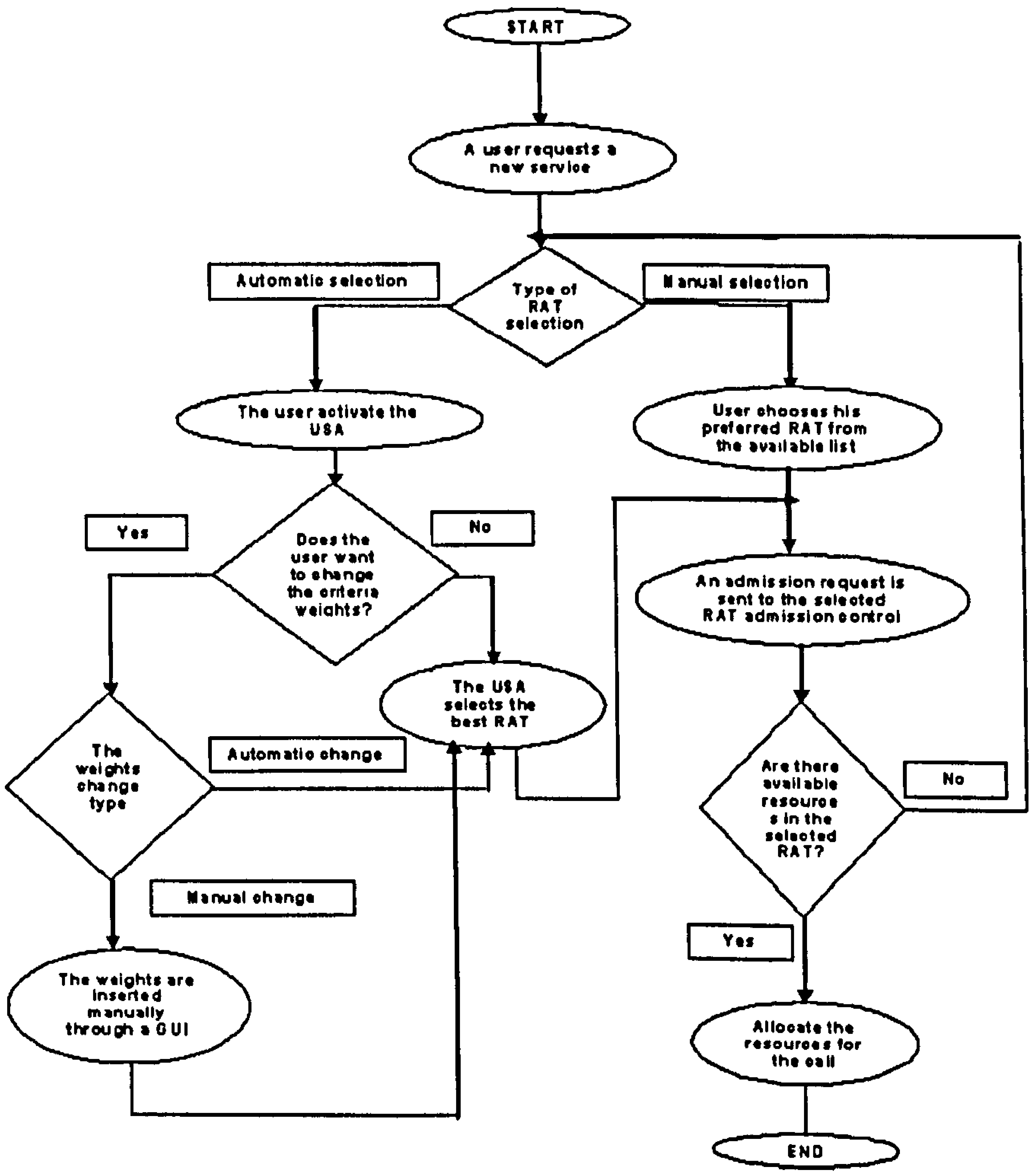

Figure 3.2: New service request in a non-coupled or multi-operator loose coupled environment NGWN

1. When the MT is turned on, a list of the available networks is detected. While roaming in the HWN, any new detected RAT is added to the available list.

2. When the user asks for a new service, the user has two available options.

   (a) In the first option, the user selects the AN from the list of the available networks manually. After the authorization of the user on the selected network, the local admission control of the selected network takes the next action by accepting or rejecting the allocation of the needed resources.

(b) In the second option, the user activates the User Software Assistant (USA) that resides in his equipment to select the best AN according to a pre-specified weighted criteria. The selection has to be sent to the selected network to authorize the user and allocate the required resources. The weights of the criteria can be assigned manually or automatically using an optimization component on the USA.

3. If the user request has been blocked, the user has to send his/her new selection again.

3.3.2 Case 1 in Scenario II and Scenario III

In this case, a new service request in a single operator loose coupled or tight/ very tight coupled HWN triggers the initial ANS module. The main steps and interactions in this case can be shown in figure 3.3 and are explained as follows:

1. When the MT is turned on, a list of the available networks is detected. While roaming on the HWN, any new detected RAT is added to the available list.

2. As in scenario I, when the user asks for a new service, the user has two available options, either manual or automated selection. In both cases, the user is authorized and the selection is sent to the CRRM or the JRRM entity in the HWN.

3. The user selection is sent to the Operator Software Assistant (OSA) resides in the CRRM or JRRM entity. At the same time, the user selection is used as one of the criteria inputs in the OSA. The importance of the user preferred selection is specified using the weight of the user preferences criteria in the OSA. Furthermore, the operator can set the weights for the input criteria either manually or optimize the weights automatically using the optimization component in the OSA. Actually the weight of the user preferences criteria in the OSA can be different from one user to another according to his/her priority and a Service Level Agreement (SLA) with the operator.

4. The OSA chooses the most suitable AN and assign it to the user. Then, the OSA asks the joint resource allocation module or the local resource allocation module of the selected network to assign the required resources to the user.

5. If the user request has been blocked, the OSA has to find another possible selection.

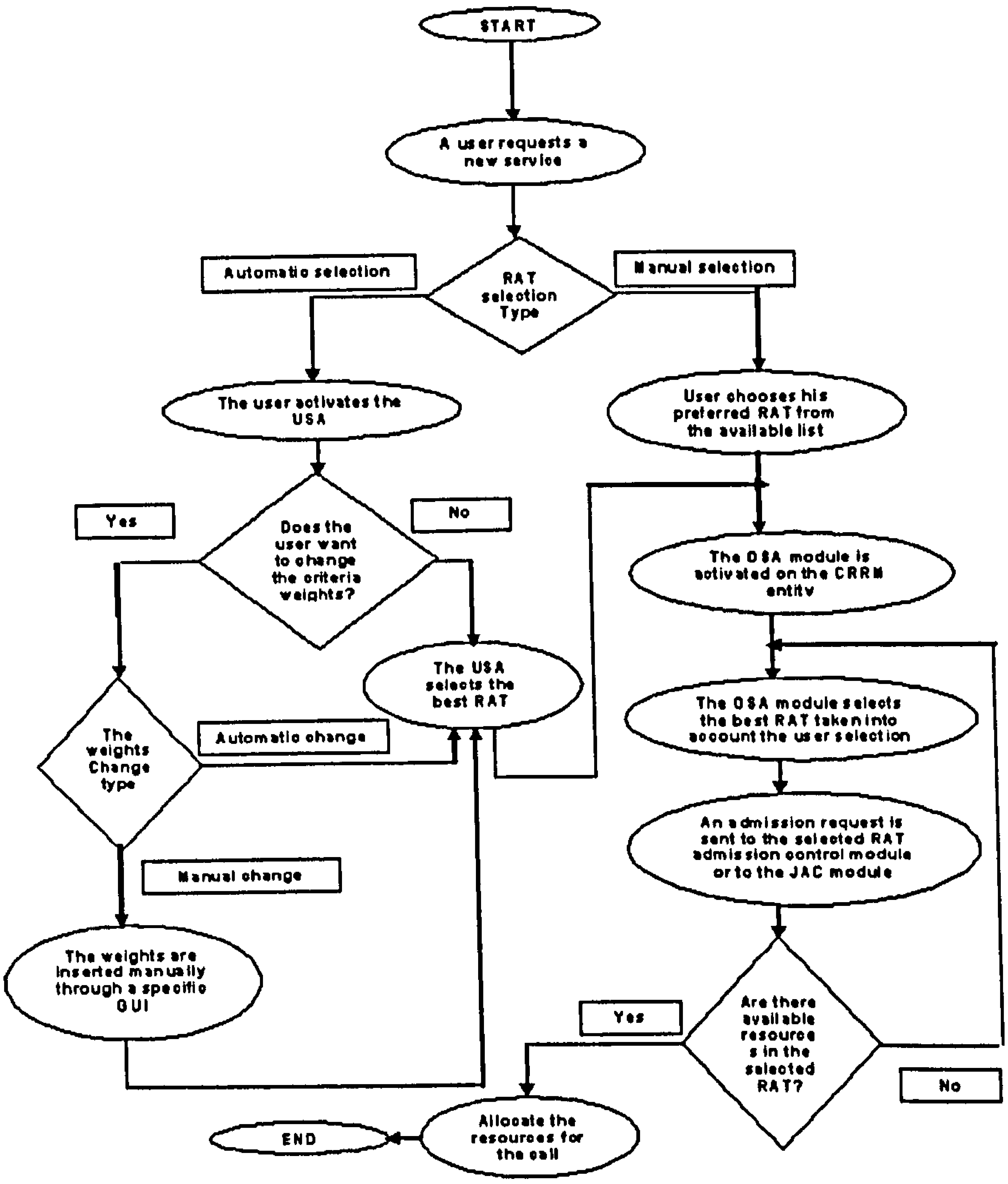

Figure 3.3: New service request in a single operator loose coupled or tight/ very tight coupled NGWN

3.3.3 Case 2 in all Scenarios

In this case, the VHO module is triggered when the VHO criteria is fulfilled. In no-coupled or loose-coupled NGWN, VHO is not possible. In the tight or very tight coupled NGWN, the process of selection in the VHO case is usually transparent from the user. The decision is taken in the CRRM/JRRM entity, but the VHO solution has to take the user preferences into account. This case is not addressed because VHO is out of this study scope.

3.3.4 Case 3 and Case 4 in all Scenarios

In case 3, the user changes his/her preferences. The user can change his/her preference in his/her equipment at any time using a suitable Graphical User Interface (GUI). In a non-coupled or loose coupled NGWN, if there are such changes, this affects the new service requests from the next request. For already running services, since no VHO is available, the change may drop the service and then the user has to select a new network according to scenario I. In a tight or very tight coupled NGWN, if there are such changes, this affects the new service requests from the next request. For already running services, this change is sent to the VHO module in the CRRM entity to check the possibility of VHO.

In case 4, the availability of a new AN is detected in an NGWN. This availability affects both the initial ANS and vertical handover selection from the next new service or VHO requests.

3.4 The ANS Problem Solving Framework

A generic and novel framework to solve the ANS problem and any other similar optimized selection problem is presented in this section. The framework consists of three main components, the first and second components are mandatory and the third component is optional. The first component contains a set of small and parallel FL systems that receive the measurements of the different ANS criteria from the different sources including the operator policies, the user preferences, the QoS requirements, and/or the RATs conditions. The second component is a Multiple Criteria Decision Making (MCDM) system and the third component is a GA component to assign weights for the criteria in the second component.

Although Figure 3.4 shows the generic framework when applied to the ANS problem, the framework can be used for any type of optimized selection problems and the changes will be on the input criteria only. The proposed framework can be used to build several user or operator ANS algorithms with several sets of criteria and different number of RATs. The framework can be described in more details as follows.

- The framework considers a heterogeneous wireless environment that contains up to n RATs (RAT_1, RAT_2, .. RAT_n). The solution that is based on the frame-

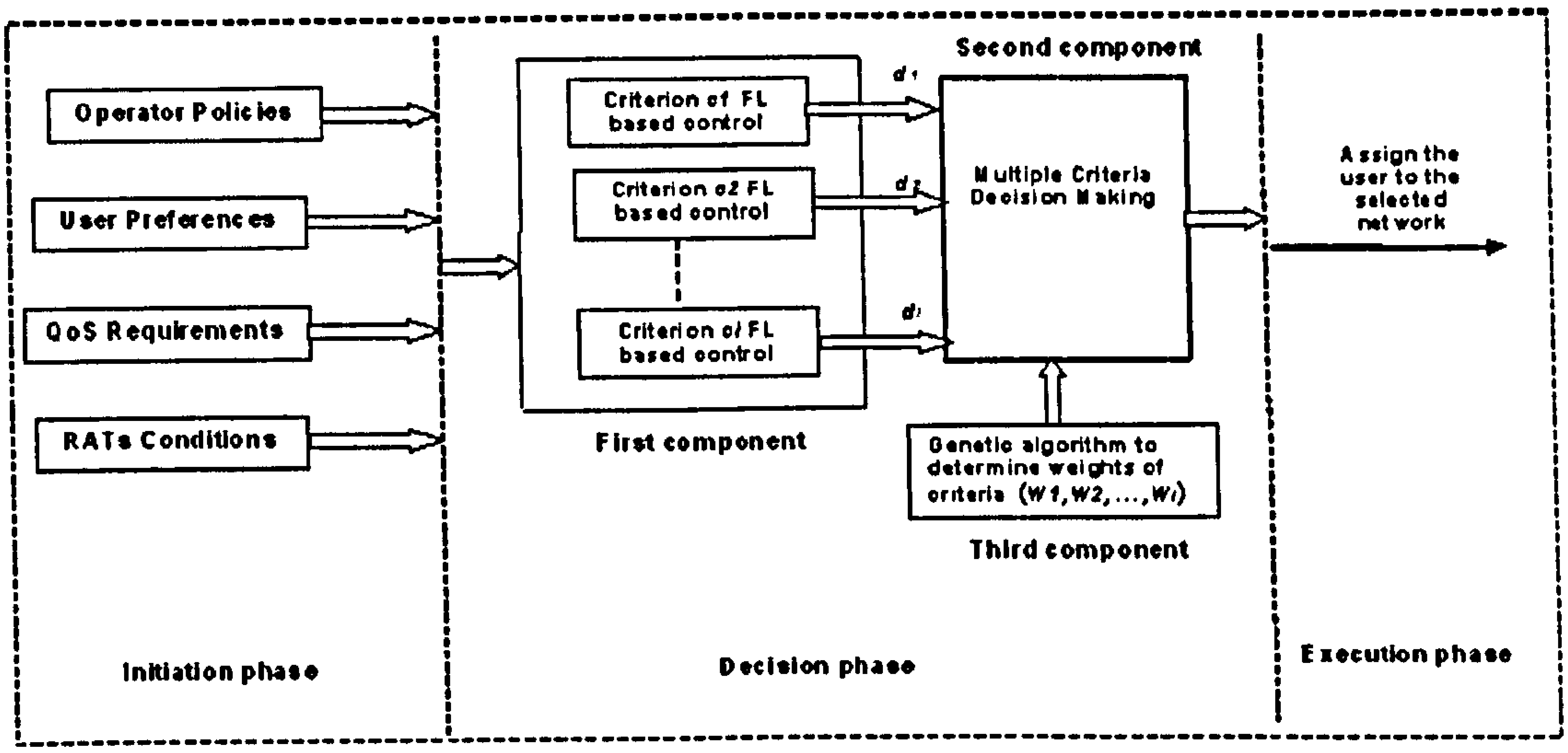

Figure 3.4: Generic ANS problem solving framework

work has to select the most promising RAT or rank the RATs according to their attractiveness.

- In the initiation phase, the need for ANS is recognized and subsequently the ANS process is initiated and the required information and measurements are gathered from the suitable sources including the operator policies, the user preferences, the QoS requirements, and the RATs conditions.

- The first component of the framework contains i parallel FL systems (FLS_1,FLS_2, .. FLS_i). Each system is used to rank the RATs based on one single criterion. The selection depends on multiple criteria up to i (c_1, c_2, .. c_i). Each criterion value is measured in the initiation phase and passed to its corresponding FL system. Every FL system gives an initial score for each RAT (d_{set1}, d_{set2}, .. d_{seti}) to reflect the attractiveness of that RAT according the FL system criterion.

- The different sets of initial scores (d_{set1}, d_{set2}, .. d_{seti}) results from the first component are sent to the MCDM in the second component. The MCDM has n alternatives (i.e. RAT_1, RAT_2, .. RAT_n) and i criteria (i.e. c_1, c_2, .. c_i). The criteria values are the initial alternatives scores given by the first component (i.e. d_{set1}, d_{set2}, .. d_{seti}). The MCDM selects the most promising RAT or ranks the available RATs according to their attractiveness.

- The weights of the criteria in the MCDM component can be assigned manually or using the GA ability in the third component. The GA component assigns suitable weights (w_1, w_2,.. w_i) for each criterion according to objective functions that reflect the importance and the sensitivities of ANS criterion to the different characteristics of the wireless heterogeneous environment.

3.5 The Justifications of the Framework Design

This section justifies the usage of the parallel FL control, MCDM, and GA in our framework. It summarizes the main advantages of applying such AI techniques to the ANS solutions.

3.5.1 The Usage of FL in the ANS Solutions

The framework utilizes the advantages of the application of FL to the ANS problem that can be summarized as follows:

- The data, information, and measurements that have to be taken into account in the ANS are in general very dissimilar, imprecise, contradictory, and coming from different sources. For example, some input parameters such as the received signal strength, the cell loads, and the SNR from different RATs, are not directly comparable. FL is tolerant of imprecise data and it allows imprecise and contradictory inputs. As a result, an FL based solution is thought to be a good candidate for reaching suitable ANS decisions from such imprecise and dissimilar information.

- Because of the complex nature of the NGWN, any proposed ANS has to allow the solution of the ANS problem in a simple way and to avoid the complex analytical and mathematical equations used in the conventional solutions. FL is conceptually easy to understand and easy to apply. The mathematical concepts behind fuzzy reasoning are very simple. The simplicity of the FL helps in providing the required simple ANS solution.

- FL reconciles the conflicting objectives of the operators, users and applications about the ANS.

- The ANS solution has to response to the changing conditions of the NGWN environments and to the accumulated experience of the operators and users. The FL based solution is easy to modify by tuning and adjusting the inference rules or the membership functions.

- The use of linguistic variables and inference rules makes the FL based solution similar to the way humans think, which makes it more intelligent and powerful than the conventional algorithm. This also can help in easy incorporation for the accumulated operator and user knowledge about the ANS problem.

3.5.2 The Usage of Parallel FL in the ANS Solutions

Applying the parallel FL rather than the traditional FL has some advantages when applied to the ANS problem. The expected huge complexity involved in the heterogeneous environment is greatly reduced using the idea of the parallel FL systems that reduce the number of needed inference rules and the complexity of each rule. We avoid the exponential increase of the rule base and thus the increase in the complexity of the system, when the number of input variables increases. To illustrate this point, assume that we have only two RATs, five inputs per RAT to one fuzzy control system and every input has 3 membership functions, then we will have up to 3^{10} inference rules. In our scheme if we use five parallel FL systems with the same inputs and number of RATs, we will have up to $5*3^2$ rules only.

In addition, the idea of the parallel FL reduces the complexity of the inference rules used in the fuzzy based solutions. To illustrate this point, assume that we have five inputs per RAT to one fuzzy control system in an NGWN that has two RATs. The most complex inference rule is in the form as IF C1/N1 AND C1/N2 AND C1/N3 AND C1/N4 AND C1/N5 AND C2/N1 AND C2/N2 AND C2/N3 AND C2/N4 AND C2/N5 AND C3/N1 AND C3/N2 AND C3/N3 AND C3/N4 AND C3/N5 AND C4/N1 AND C4/N2 AND C4/N3 AND C4/N4 AND C4/N5 AND C5/N1 AND C5/N2 AND C5/N3 AND C5/N4 AND C5/N5 THEN D1 AND D2 AND D3 AND D4 AND D5, where Ci/Nj means network j rating value against criteria i and Dj means initial score for network j. However, using our parallel FL systems, the most complex inference rule could be built as IF C1/N1 AND C1/N2 AND C1/N3 AND C1/N4 AND C1/N5 THEN D1 AND D2 AND D3 AND D4 AND D5.

Furthermore, the outputs of the parallel FL systems that are in the range [0, 1] provide already normalized inputs (i.e. RATs rating against criteria) for the MCDM. This provides great advantage over the previous MCDM based solutions that need to normalize their input data with some inappropriate methods.

3.5.3 The Usage of MCDM in the ANS Solutions

Our framework utilizes the advantages of the application of MCDM to the ANS problem that can be summarized as follows:

- In a very complex and uncertain environments such as NGWN, MCDM can sufficiently reduce the uncertainty and doubt about the alternatives and allows a reasonable choice to be made from among them.
- The ANS decision deals with making a selection among a limited number of candidate networks from various service providers and technologies with respect to different criteria. Hence, it is a typical MCDM problem and it is not practical to apply a single criterion based solution to such a problem.
- The ANS problem is a multi-criteria problem in nature and the flexibility and complementary ANS multi-criteria have to be utilized to provide a solution that can cope with the different viewpoints and goals. If suitable weights have been assigned for each criteria using GA, the user satisfaction average and the operator benefit can be maximized at the same time. This makes the proposed solution more efficient than the traditional algorithms that are either user-centric or operator-centric.
- The MCDM is a flexible tool, because the weights of the different criteria can be tuned easily. If the operator or user gains more knowledge about the ANS problem and its sensitivity to the different criteria, it will be easy to incorporate this knowledge to the existing ANS solution.

3.5.4 The Usage of GA in the ANS Solutions

In our study the GA is used to overcome one of the MCDM drawbacks, which is the finding of suitable weights for the different criteria. The following points summarize the main advantages of applying the GA to the ANS problem.

- GA can deal with the large number of variables and the complex search space included in the ANS criteria weights with high probability of success in finding an optimal, near optimal or at least a good solution.
- GA can handle the different constraints and objectives of the ANS criteria weights.

- GA does not require derivative information, which can help in the user ANS algorithm where not enough data exists due to the limitation of storage in the mobile terminal.
- GA is less likely to be trapped by local optimal minima or maxima.
- GA works with numerically generated data, experimental data, or analytical functions. This can give different options when designing the ANS algorithm.

3.6 Discussion

In the first part of this chapter, a comprehensive analysis for the ANS process in the different HWN coupling scenarios is provided. At each scenario, the roles and rights of the users and operators are clarified. Then, the different cases that could trigger the ANS module are presented. The blueprints of the ANS process in each case are drawn. It is obvious that both the user and operator want to control the process of the ANS and their roles have to be different according to the coupling degree between the co-existing RATs in the NGWN.

In the second part of this chapter, the details of an intelligent and generic framework to solve the optimized selection problems are described. The new framework is feasible in terms of adaptability, scalability, simplicity, overhead, and generality.

In terms of adaptability (i.e. learning); the framework can react to the NGWN changing environment conditions and accumulated human knowledge using different methods. One method is by tuning the FL rules and membership functions, where neural networks (NN) or GA can be used. Another method is by adapting the weights of the MCDM system that are assigned either manually or using GA. To use GA in the weights adaptation, the operator can build any objective function and the GA could find suitable weights. In the terminal-controlled algorithm, the user could be offered several built-in objective functions where the user can choose the suitable one for him/her.

With respect to scalability; the framework tries to achieve scalability by reducing the number and complexity of FL inference rules. Hence, increasing the number of RATs or number of criteria could be easy and the framework can achieve a large number of inputs and criteria. To illustrate this point, assume that we have a user ANS algorithm based on four criteria and two RATs. Let's assume first that we need to increase the number of criteria to five, what is needed here is a new and small FL system that will not affect the other existing FL modules in the parallel FL system. The MCDM needs no change, because the number of criteria i can be set as a variable integer number in the programming code and the decision matrix dimensions (i.e. i and number of RATs j) are also integer variables. The GA number of variables and objective functions could be built to be adaptive and scalable.

The complexity of the framework can be measured by the number and type of the calculations required to achieve it. The number of the operations in our selection decision is low enough to ensure operation in real time by means of software approaches. The types of calculations are essentially comparisons and summations with a small number of multiplications and divisions.

In terms of the required amount of overhead (signalling); big overhead results from signalling whilst collecting the required measurements from different sources. Additional overhead results from transferring the control information between the CRRM, user terminal and local RRM entities to finalize the selection decision. The framework tries to minimize this overhead by dividing the selection process into two algorithms. It allocates the user algorithm on the user terminal and the operator algorithm on the CRRM entity. If the selection criteria are chosen carefully in both algorithms, the required signalling for collection the measurements can be greatly reduced.

In terms of generality; the framework is applicable to any type and number of ANs. Any type of criteria either subjective or objective and any kind of inputs either quantitive or qualitative could be used. In addition, the framework could be used for any other type of optimized selection problems.

In the next two chapters, two operator ANS algorithms are developed. Both algorithms are based on the developed framework in this chapter. The efficiency of both algorithms is addressed by means of performance metrics that reflect the user satisfaction, the operator benefits, and the QoS conditions.

User ANS has not been built in this study. In fact, the user ANS algorithm is much easier to evaluate and simulate than the operator ANS algorithm because it depends on user subjective criteria where no need for complex simulation and evaluation environments.

Chapter 4

Combined FL and SMART MCDM for Operator ANS Algorithm

Based on our developed framework on chapter 3 and based on the new roles that are suggested for both users and operators in the same chapter, a User Software Assistant (USA) with suitable input criteria can be developed and used in the UE. An Operator Software Assistant (OSA) based on the same framework with suitable input criteria can also be developed and used in the operator CRRM or JRRM entity. Both OSA and USA are based on the same framework and the main difference is in the used input criteria.

Since the user has the total right to make the selection in both non-coupled and multi operator loose coupled HWN, only the USA is needed in this type of environments. As both the user and the operator share the rights for selection in the single operator loose coupled, cooperative multi-operator loose coupled, and in the tight or very tight coupled HWN, both USA and OSA are needed.

OSA based in our framework (that is outlined in chapter 3) is developed in this chapter. The developed OSA deals with a wireless environment that contains a co-existed WWAN and a WLAN networks and are based on parallel FL and SMART MCDM tool. Four criteria are used in the OSA, namely, the Received Signal Strength (RSS), the Mobile Station Speed (MSS), the Service Type (ST), and the User Preferences (PRICE). The RSS criterion reflects the networks conditions viewpoint because weak received signal can cause unnecessary handover, call drop, and packets or bits errors. The MSS criterion reflects the viewpoint of the operators because connecting the slow users to the small coverage area ANs and the fast users to the larger coverage area ANs will avoid unnecessary handover overhead and will save the networks' resources. The ST criterion reflects the viewpoint of the application and services requirements. The PRICE criterion reflects the user viewpoint because the users may prefer to select one network among others due to its low price or their previous satisfaction.

An important consideration when selecting the criteria was to ensure that all important criteria related to the ANS are included. We have tried to keep the number of criteria to the minimum consistent with making a well-founded decision. The criteria that have been judged relatively unimportant (i.e. all of the alternatives are likely to achieve the same ranking when assisted against it) or to be duplicated have been avoided. Mutual independence between criteria has been considered, where the preference score of alternatives with respect to one criterion is assigned, without knowing the preference scores of alternatives with respect to the other criteria.

It is worth mentioning that the PRICE criterion could be the output of another USA that reflects the user point of view on the selection process. The weight of this criterion also can be controlled by the operator according to an SLA between both user and operator (i.e. the more important user can be given high value for the weight of PRICE criterion and the less important user can be given lower value).

Resource Availability (RA) is another important criterion that could be considered when accepting or rejecting the new or handoff service request. However, RA is usually considered at the admission and resource allocation stage by the local or common admission and load control algorithms. In fact, we think it would be more desirable to consider the RA criterion at both the initial selection stage and the resource allocation stage. In the initial selection stage, the network with more available resources has more credits to be selected for the new service request. In the resource allocation stage, the required resources for the new or handoff service are allocated from the low congested network. However, our developed algorithm assumes that this criterion is usually treated by the local or common admission control and our solutions do not consider it.

The details of the developed OSA are shown in Figure 4.1. Our OSA contains four parallel FL based systems. Each system considers one of the ANS proposed criteria. The four FL systems are the RSS system to consider the received signal strength criterion, the MSS system to consider the mobile station speed criterion, the ST system to consider the service type criterion, and the PRc system to consider the user preferred PRICE criterion. The outputs of the four parallel systems are used as the preference scores for the alternatives in the SMART MCDM component. The following sections describe the four FL components and the MCDM component. The last section of this chapter illustrates the developed ANS algorithm by means of several numerical examples.

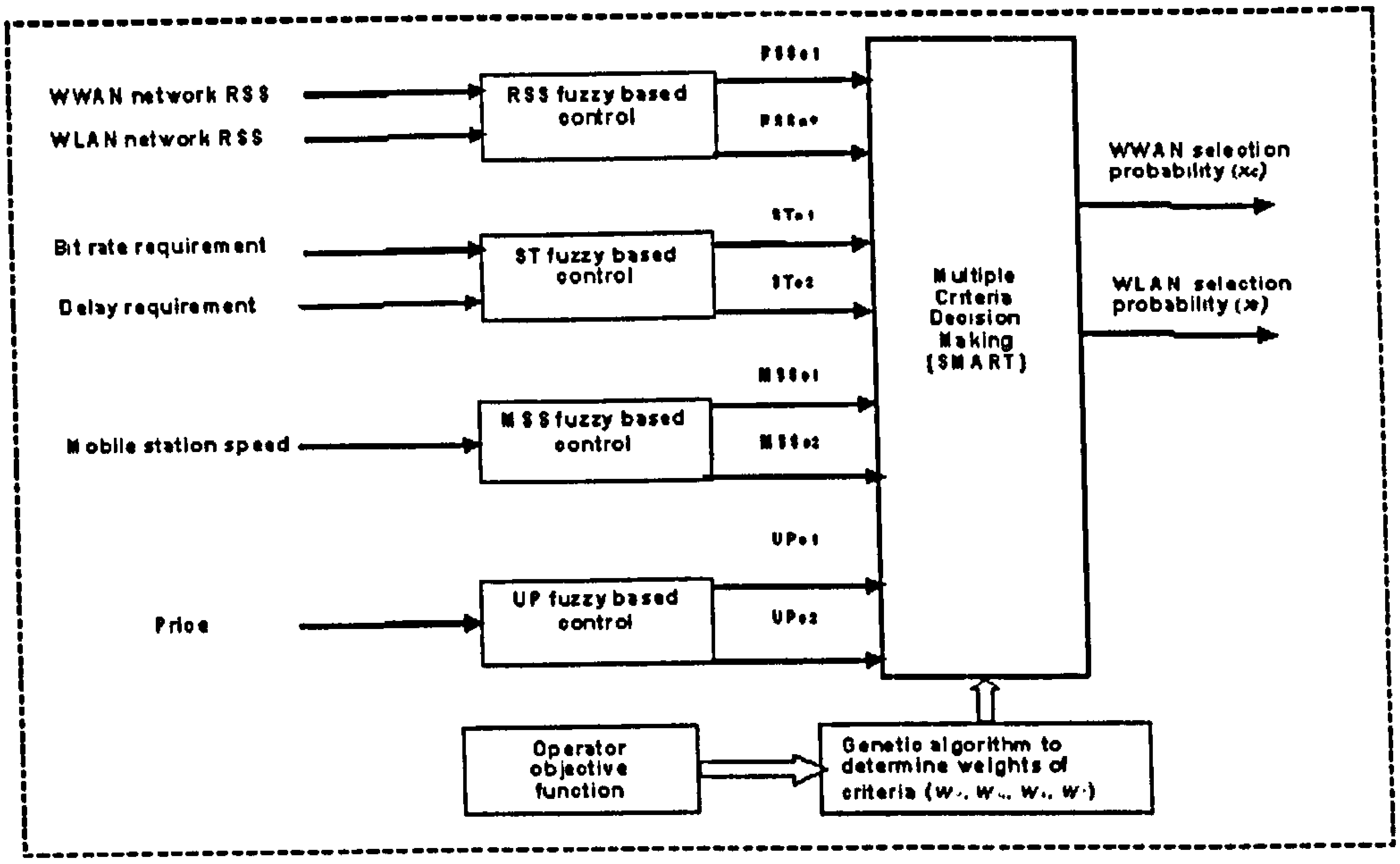

Figure 4.1: ANS OSA for co-existed WWAN and WLAN systems

4.1 The RSS FL based System

The RSS FL based system considers the RSS criterion. The RSS criterion reflects the networks conditions viewpoint because weak received signal can cause unnecessary handover, call drop, and packets or bits errors. Figure 4.2 shows the RSS FL system. The figure shows that the system has two input variables "RSS_1" and "RSS_2" and it has two output variables "RSS_{c1}" and "RSS_{c2}".

4.1.1 The Inputs Definition

The input variable "RSS_1" describes the received signal strength from the WWAN and the input variable "RSS_2" describes the received signal strength from the WLAN. The universe of discourse contains all the inputs and outputs that can come into consideration. The universes of discourses of the input variables are selected based on the manuals and operation instructions of existed networks such as IEEE802.11, UMTS, GSM, and GPRS. The universe of discourses of "RSS_1" and "RSS_2" start with the weakest signal that could be sensitized by mobile terminal (i.e. -110 dBm). They end with the

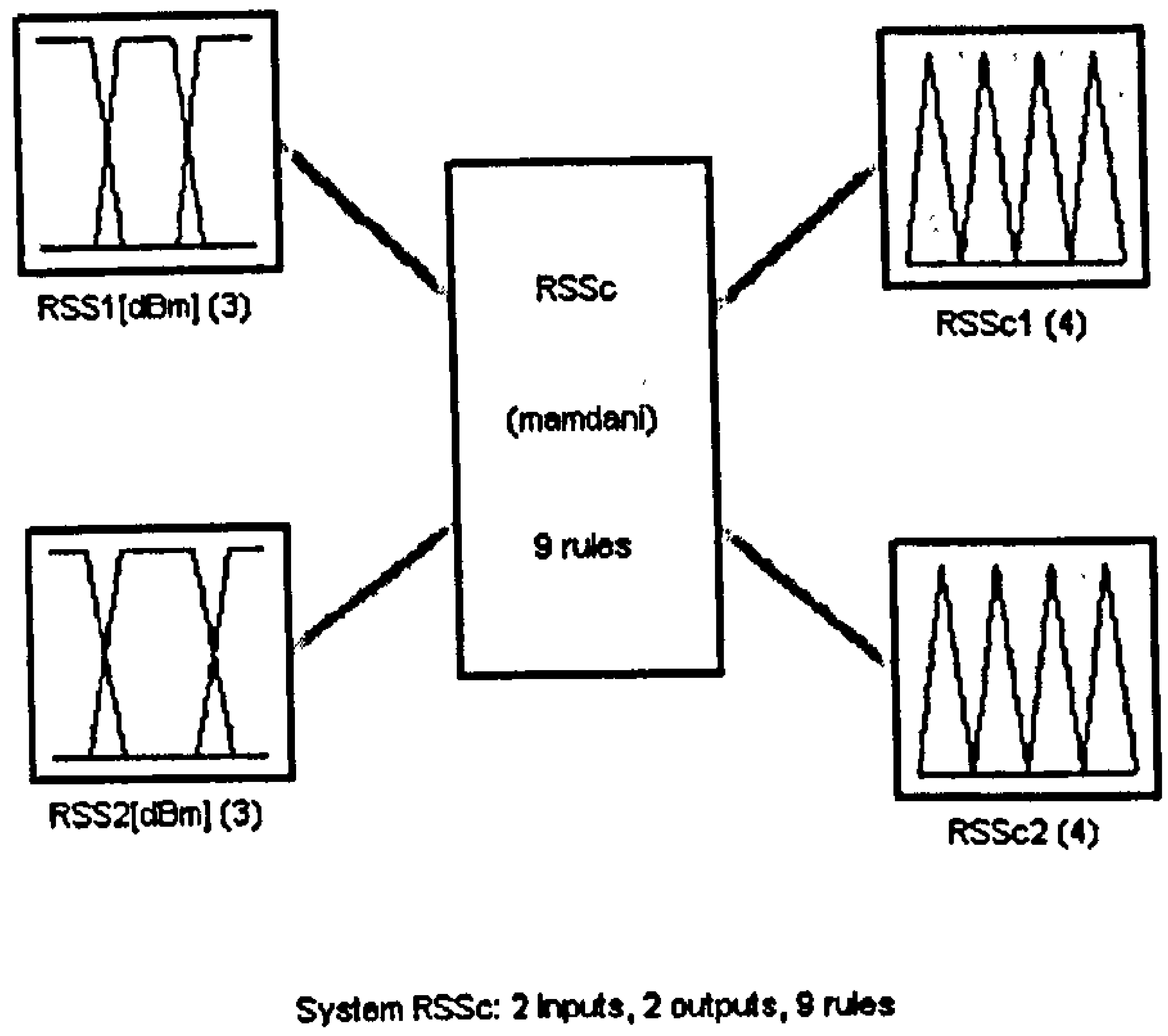

Figure 4.2: The RSS FL system

strongest signal that could be received by the mobile terminal and transmitted by the base station (i.e. -70 and -50 dBm).

Two important considerations are considered when deciding the universe of discourse of the input variables. The first consideration is to make sure that the universe is not too small, so the input will not be off the scale. The second one is to make sure that the universe is not too wide, so the membership function in both left and right will not affect the overall system performance when trying to capture the rare extreme input values. Any data out of the range are quantized to the nearest value at the most right or most left of the universe. Each universe of discourse is described using three linguistic variables {Low, Medium, High}. The linguistic variable "Low" indicates low signal strength, the variable "High" indicates high signal strength, and the variable "Medium" indicates medium signal strength.

4.1.2 The Membership Functions of the Inputs

In the membership function choice, one has to solve a few problems: how to choose the number of membership functions to describe all the values of the linguistic variable on the universe, the position of different membership functions on the universe of discourse, the width of the membership functions, and the shape of a particular membership function. In this subsection, we present suitable answers for the above questions. We develop the most suitable membership functions that reflect the desirable features and goals of the ANS process. The number, the position, the width, and the shape of the membership functions have been illustrated mathematically by means of sutiable mathematical equations.

Due to their computational simplicity, the used membership functions in our solution (to describe the linguistic variables) are triangular or trapezoidal shaped. These types of shapes are a standard choice used in many industry applications due to their simple expressions. A symmetric triangular membership function is shown in Figure 4.3, where L and R are the left and right bounds, respectively, and C is the centre of the symmetric triangle.

$$\mu_{triang}(x) = \begin{cases} 0 & x < L \\ 1 - \dfrac{|C - x|}{(R-L)/2} & L < x < R \\ 0 & x > R \end{cases}$$

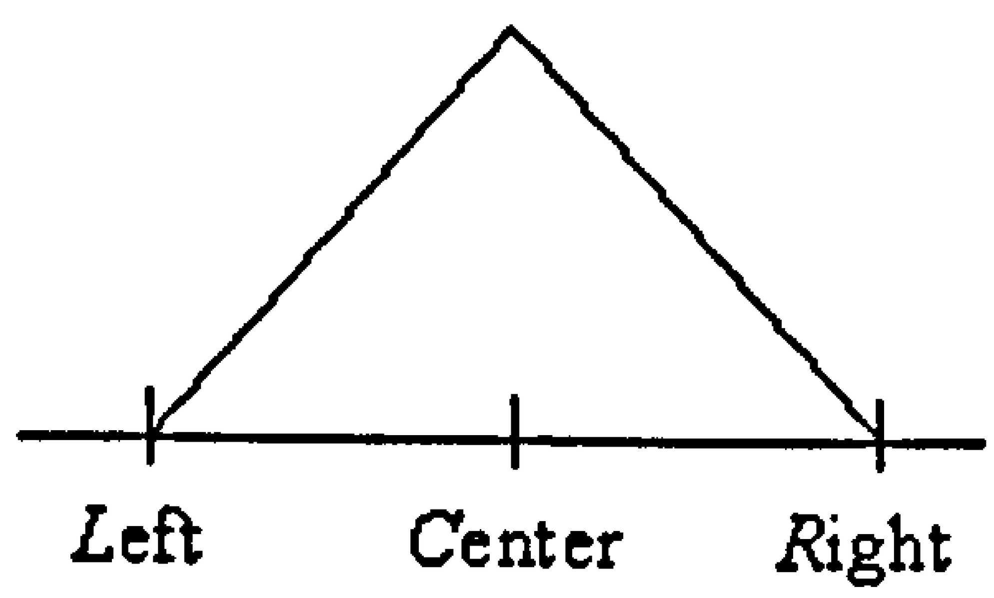

Figure 4.3: A symmetric triangular membership function

A symmetric trapezoidal membership function is shown in figure 4.4, where L and U are the lower and upper bounds, respectively, C is the centre, and W is the width of the top side of the symmetric trapezoid.

$$\mu_{trapez}(x) = \begin{cases} 0 & x < L \text{ or } x > U \\ \dfrac{x - L}{C - W/2 - L} & L < x < C - W/2 \\ 1 & C + W/2 < x < C + W/2 \\ \dfrac{U - x}{U - (C + W/2)} & C + W/2 < x < U \end{cases}$$

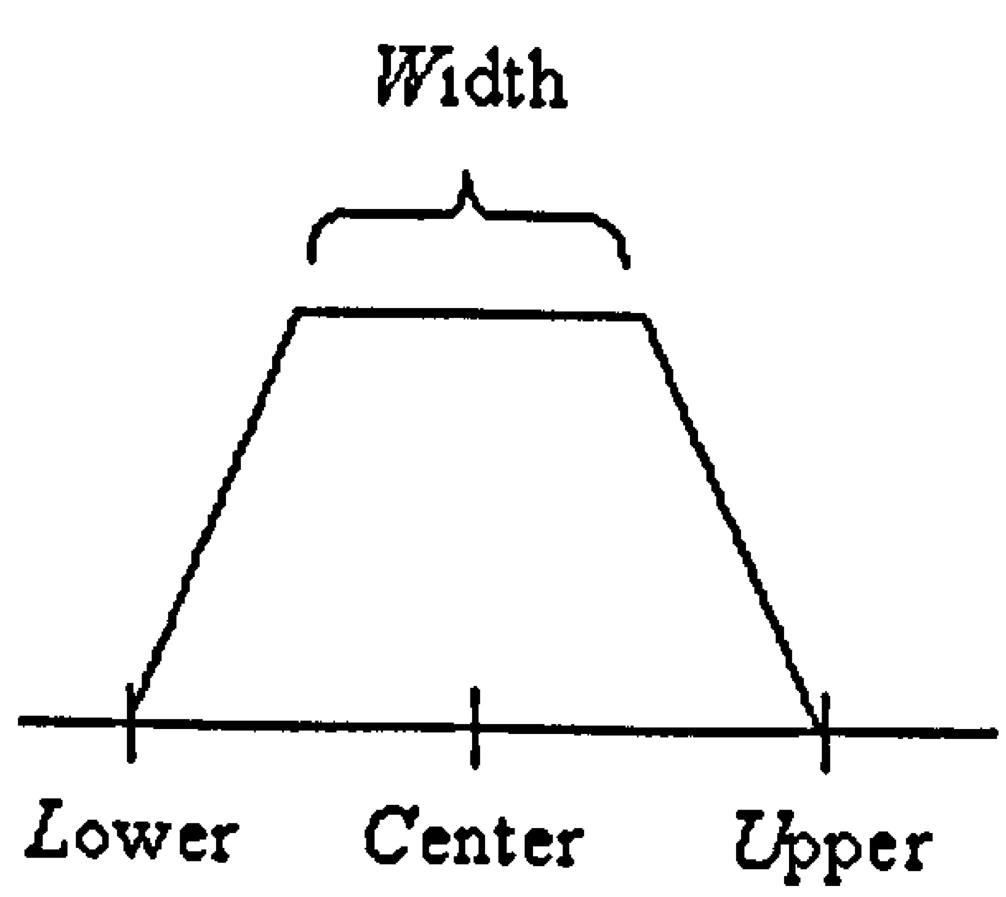

Figure 4.4: A symmetric trapezoidal membership function

Both input variables have three membership functions {Low (L), Medium (M), and High (H)}. The membership functions of the variable "RSS_1" are described mathematically as in equations 4.1, 4.2, and 4.3. Figure 4.5 shows the membership functions of the variable "RSS_1". Certain amount of overlapping between the membership functions is considered to avoid poorly defined output state.

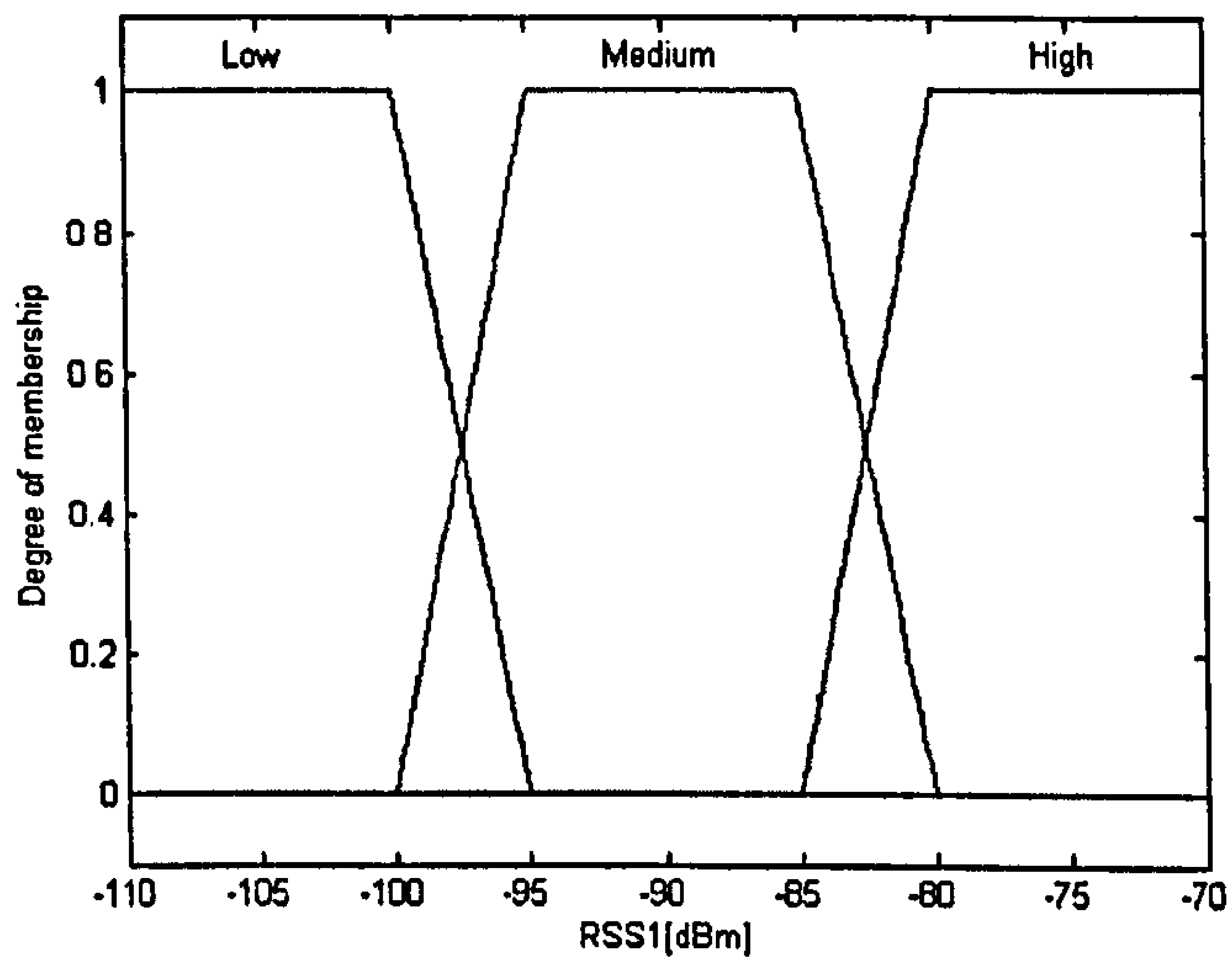

Figure 4.5: The membership functions of the input variable "RSS_1"

$$\alpha_L(RSS1) = \begin{cases} 1 & \text{if } RSS1 < -100 \\ \frac{-100-RSS1}{-95+100} & \text{if } -100 < RSS1 < -95 \\ 0 & \text{if } RSS1 > -95 \end{cases} \tag{4.1}$$

$$\alpha_M(RSS1) = \begin{cases} 0 & \text{if } RSS1 < -100 \text{ OR } RSS1 > -80 \\ \frac{RSS1+100}{-95+100} & \text{if } -100 < RSS1 < -95 \\ 1 & \text{if } -85 > RSS1 > -95 \\ \frac{-80-RSS1}{-80+85} & \text{if } -85 < RSS1 < -80 \end{cases} \tag{4.2}$$

$$\alpha_H(RSS1) = \begin{cases} 0 & \text{if } RSS1 < -85 \\ \frac{RSS1+85}{-80+85} & \text{if } -85 < RSS1 < -80 \\ 1 & \text{if } -80 > RSS1 \end{cases} \tag{4.3}$$

The membership functions of the input variable "RSS_2" are described mathematically as in equations 4.4, 4.5, and 4.6. Figure 4.6 shows the membership functions of the variable "RSS_2". Again a certain amount of overlapping between the membership functions is considered to ensure robust inference and usually defined output state.

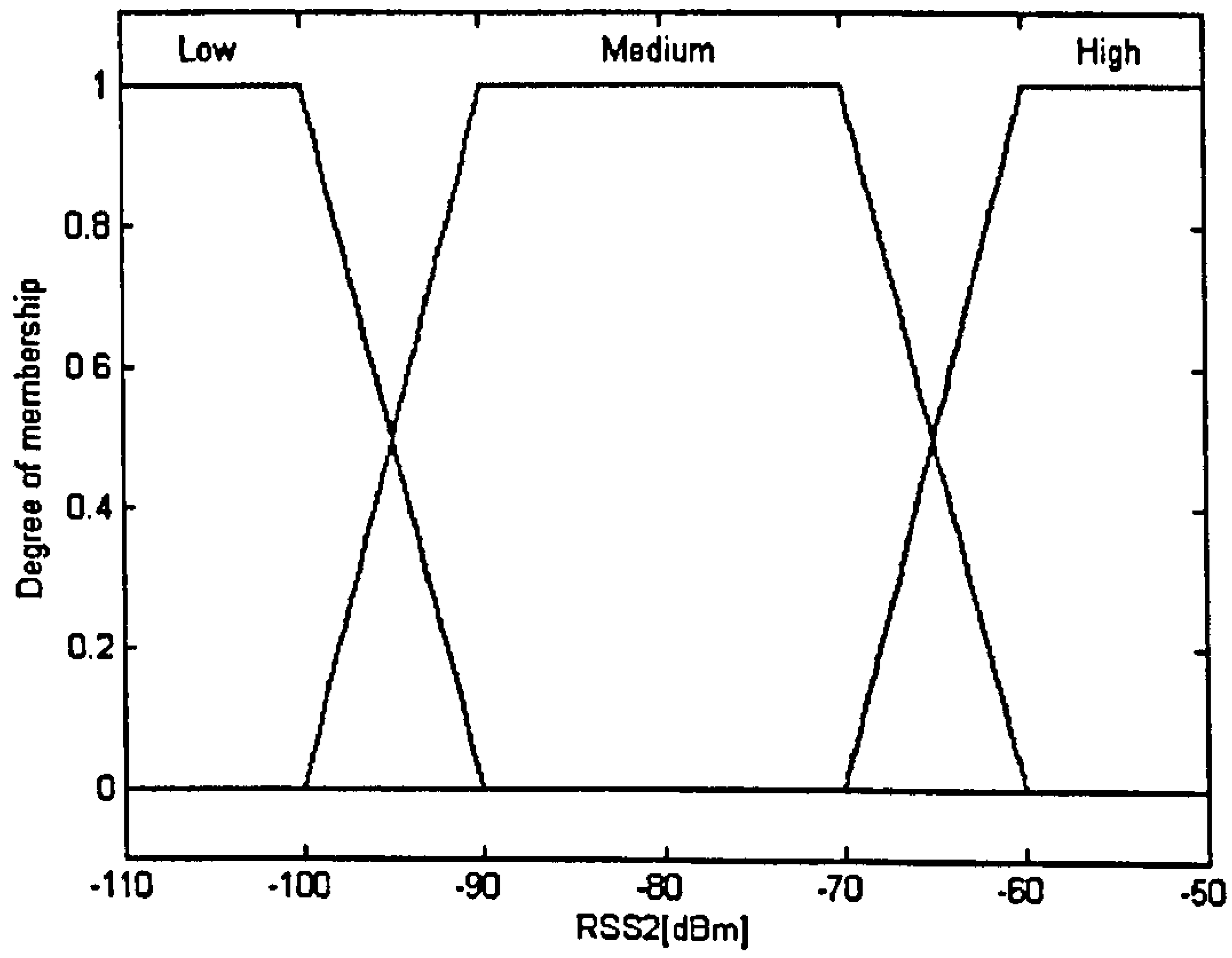

Figure 4.6: The membership functions of input variable "RSS_2"

$$\alpha_L(RSS2) = \begin{cases} 1 & \text{if } RSS2 < -100 \\ \frac{-100-RSS2}{-90+100} & \text{if } -100 < RSS2 < -90 \\ 0 & \text{if } RSS2 > -90 \end{cases} \tag{4.4}$$

$$\alpha_M(RSS2) = \begin{cases} 0 & \text{if } RSS2 < -100 \text{ OR } RSS2 > -60 \\ \frac{RSS2+100}{-90+100} & \text{if } -100 < RSS2 < -90 \\ 1 & \text{if } -70 > RSS2 > -90 \\ \frac{-60-RSS2}{-60+70} & \text{if } -70 < RSS2 < -60 \end{cases} \tag{4.5}$$

$$\alpha_H(RSS2) = \begin{cases} 0 & \text{if } RSS2 < -70 \\ \frac{RSS2+70}{-60+70} & \text{if } -70 < RSS2 < -60 \\ 1 & \text{if } -60 > RSS2 \end{cases} \tag{4.6}$$

4.1.3 The Fuzzy Inference System and Rules

The Fuzzy Inference System (FIS) of the RSS system and all other systems has the following common characteristics.

- It uses the Mamdani style FIS [127, 128].
- It uses the Min operation for AND method.
- It uses the Max operation for OR method.
- It uses the Min operation for implication.
- It uses the Max operation for aggregation.

A careful design of the rule base is done based on two goals. The first goal is the completeness of rules, which means that all kinds of situations of system behaviour are taken into consideration, i.e. all kinds of combinations of input variables results in an appropriate output value. The second goal is the consistency of the rules, which means that the rule base does not contain any contradiction. A set of rules is inconsistent if there are at least two rules with the same antecedents-part and different consequent-part. This is an obvious mistake and one of the rules must be excluded. The relationship between the inputs and the output is mainly based on intuitive understanding and considerations of the ANS goals and desirable features. The rules are tuned manually from offline system behaviour observation. Figure 4.7 shows the rules viewer that is used to tune the fuzzy inference rules.

In all systems the maximum number of inference rules are used (this is possible because the maximum number is still so small thanks to the parallel FL idea), which increases the accuracy of the approximation and yields an improved control performance.

The RSS fuzzy system rules have been built with the aim to assign the user to the network with a better signal strength. Weak received signal can cause unnecessary handover, call drop, and packets or bits errors, which in turn reduce the user satisfaction, the operator benefit, and degrade the QoS. Table 4.1 shows the nine inference rules of the RSS fuzzy system. The same form of the IF-THEN control rules has been used for the rest of the FL systems.

For example, the third inference rule illustrates that when a user is receiving a high signal from the WWAN and low signal from the WLAN, the user should be totally

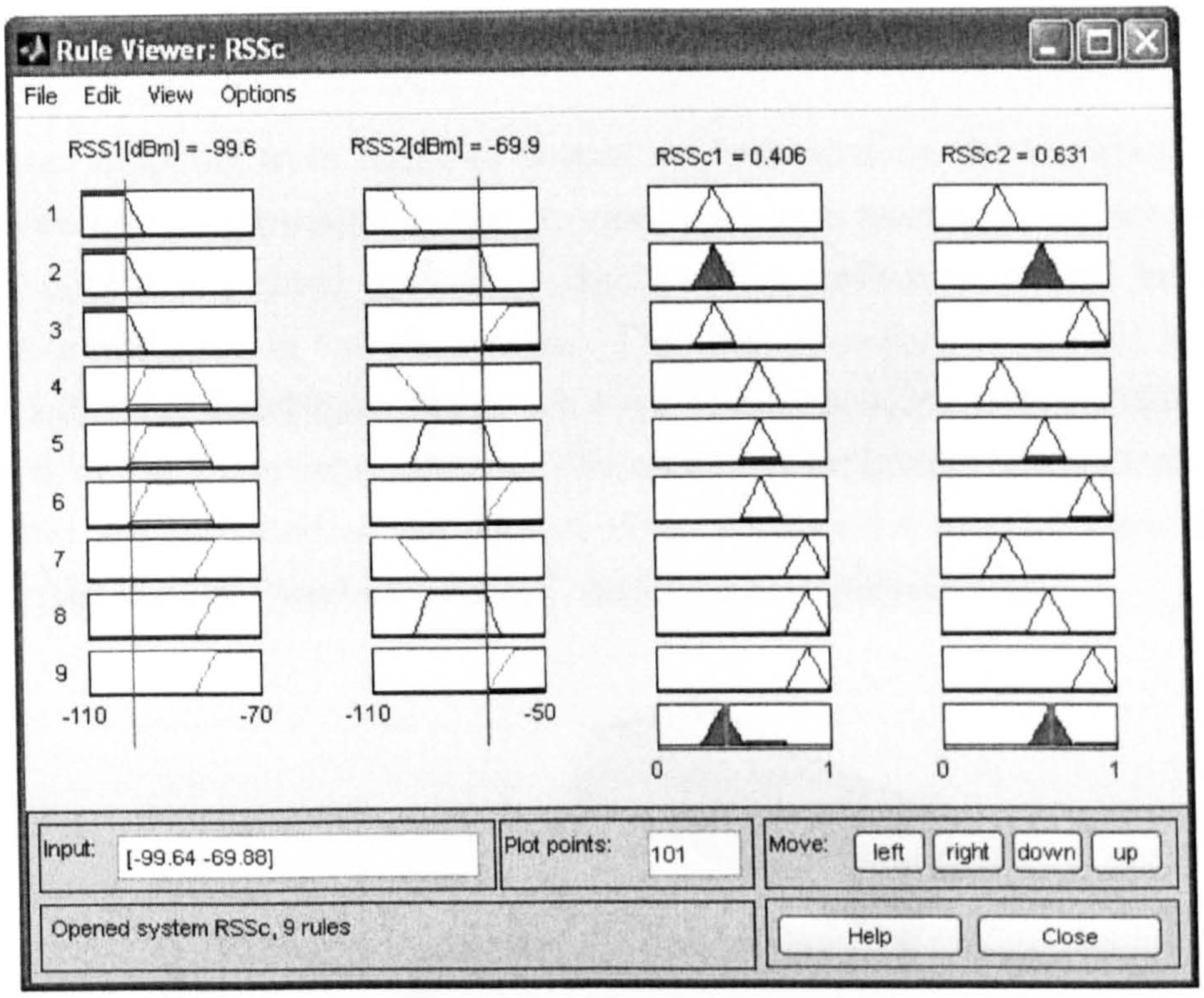

Figure 4.7: The FL inference rules viewer

Table 4.1: The inference rules of the RSS FL system

Rule No.	Rule
1	If RSS_1 is High AND RSS_2 IS High Then (RSS_{c1} is TA) (RSS_{c2} is TA)
2	If RSS_1 is High AND RSS_2 IS Medium Then (RSS_{c1} is TA) (RSS_{c2} is PA)
3	If RSS_1 is High AND RSS_2 IS Low Then (RSS_{c1} is TA) (RSS_{c2} is PR)
4	If RSS_1 is Medium AND RSS_2 IS High Then (RSS_{c1} is PA) (RSS_{c2} is TA)
5	If RSS_1 is Medium AND RSS_2 IS Medium Then (RSS_{c1} is PA) (RSS_{c2} is PA)
6	If RSS_1 is Medium AND RSS_2 IS Low Then (RSS_{c1} is PA) (RSS_{c2} is PR)
7	If RSS_1 is Low AND RSS_2 IS High Then (RSS_{c1} is PR) (RSS_{c2} is TA)
8	If RSS_1 is Low AND RSS_2 IS Medium Then (RSS_{c1} is PR) (RSS_{c2} is PA)
9	If RSS_1 is Low AND RSS_2 IS Low Then (RSS_{c1} is PR) (RSS_{c2} is TA)

accepted (TA) in the WWAN and should be rejected in the WLAN with high probability (PR).

4.1.4 The Input-Output Mapping Control Surface

The nonlinear mapping from input to output implemented by the FL system is called the control surface. This mapping can be visualized by a nonlinear surface plot, where the system output is plotted against its inputs. The surface represents in a compact way all the information in the FL system. The rippled surface is created by the rules and the membership functions. There is a type of interpolation between the rules that is performed by the fuzzy logic system. The output is an interpolation of the effects of the rules that are activated at the current time. Figures 4.8 and 4.9 show the control surfaces for the output variables "RSS_{c1}" and "RSS_{c2}" respectively.

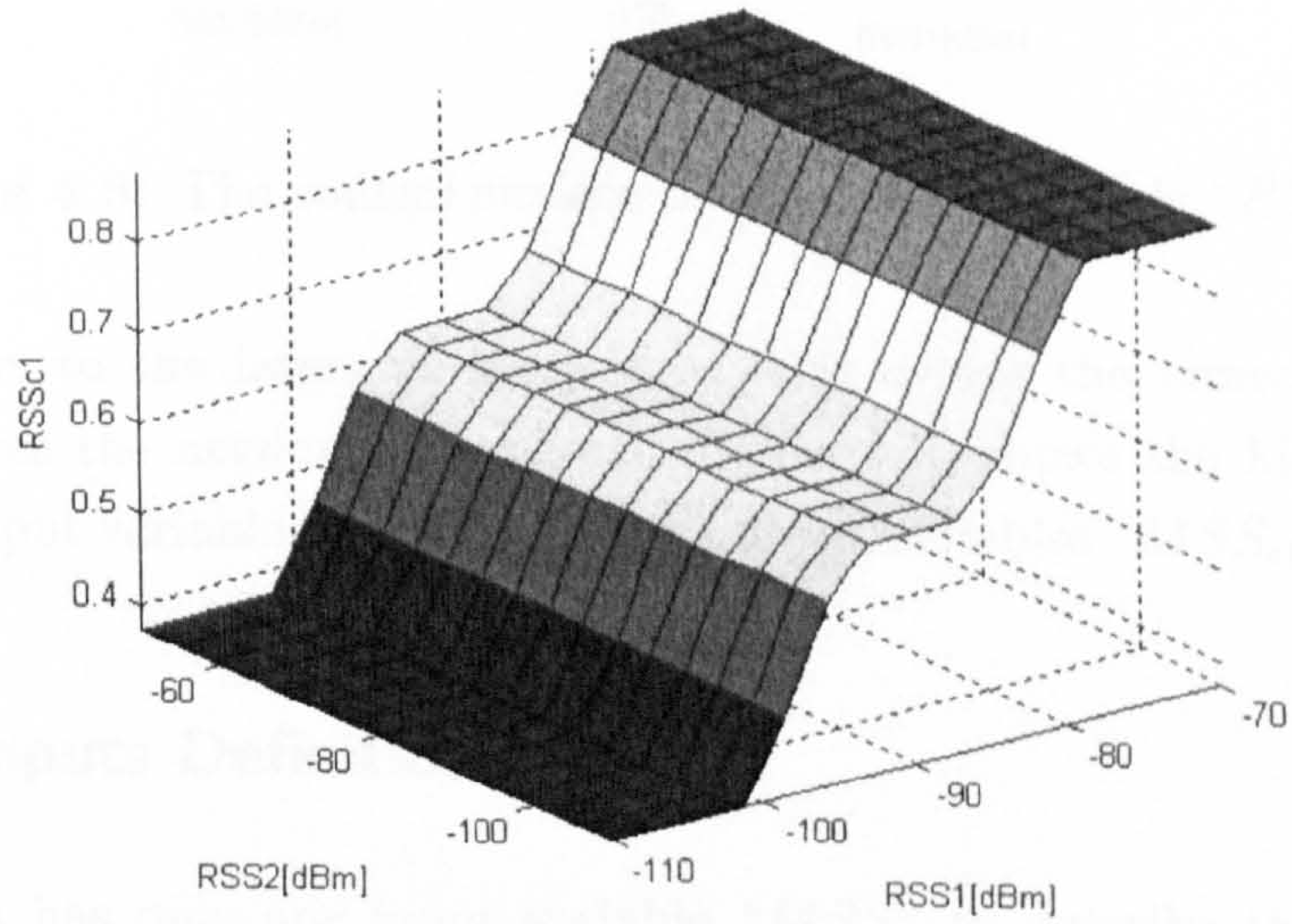

Figure 4.8: The control surface of the output variable "RSS_{c1}"

Figure 4.8 shows that with increased value for "RSS_1" the chance of selecting the WWAN network is becoming higher (i.e. "RSS_{c1}" increase) on the other hand Figure 4.9 shows that with increased value for "RSS_2" the chance of selecting the WLAN network is becoming higher. These are the expected behaviours from the RSS FL system.

4.2 The MSS FL based System

The MSS system considers the mobile station speed criteria. MSS criterion reflects the operators viewpoint because connecting the slow users to the small coverage area ANs

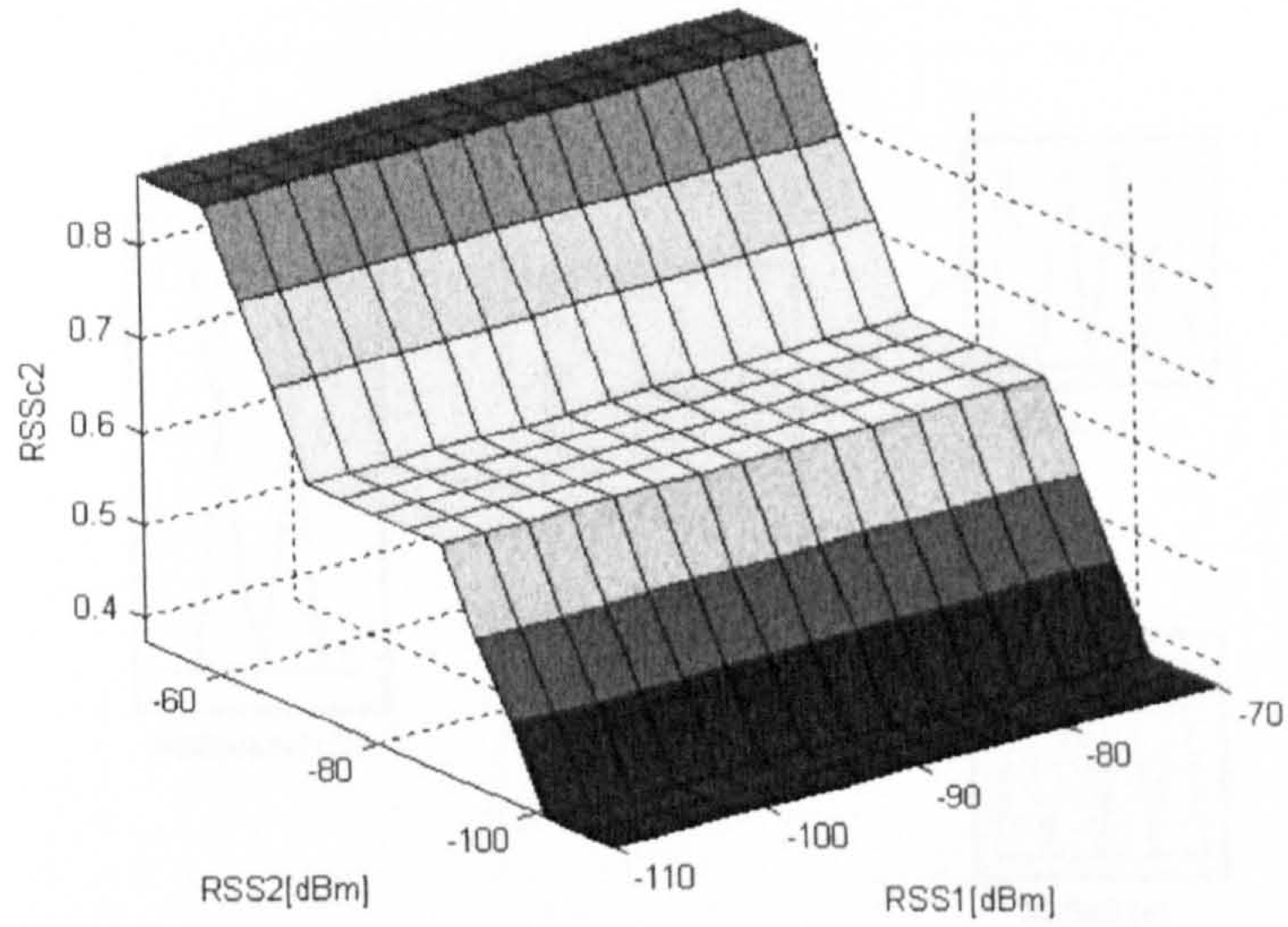

Figure 4.9: The control surface of the output variable "RSS_{c2}"

and the fast users to the larger coverage area ANs avoids the unnecessary handover overhead and saves the networks resources. Figure 4.10 shows the MSS system. The system has one input variable "MSS" and two output variables "MSS_{c1}" and "MSS_{c2}".

4.2.1 The Inputs Definition

The MSS system has only one input variable "MSS" to describe the mobile station speed. The universe of discourse is selected to represent the expected speed of a walking user. The universe begins with 0 km/hr (Kilometer per hour) to represent the stationary user and ends with the 10 km/hr to represent the speed of a running user. Three linguistic variables have been used to describe the universe of discourse {Low, Medium, and High}. The linguistic variable "Low" indicates low MS speed, the variable "Medium" indicates medium MS speed, and the variable "High" indicates high MS speed.

4.2.2 The Membership Functions of the Inputs

The membership functions of the input variable "MSS" can be described mathematically as in equations 4.7, 4.8, and 4.9. Figure 4.11 shows the membership functions of the "MSS" variable. The significant overlapping between the first and second membership function and between the second and third membership function imply smoother and

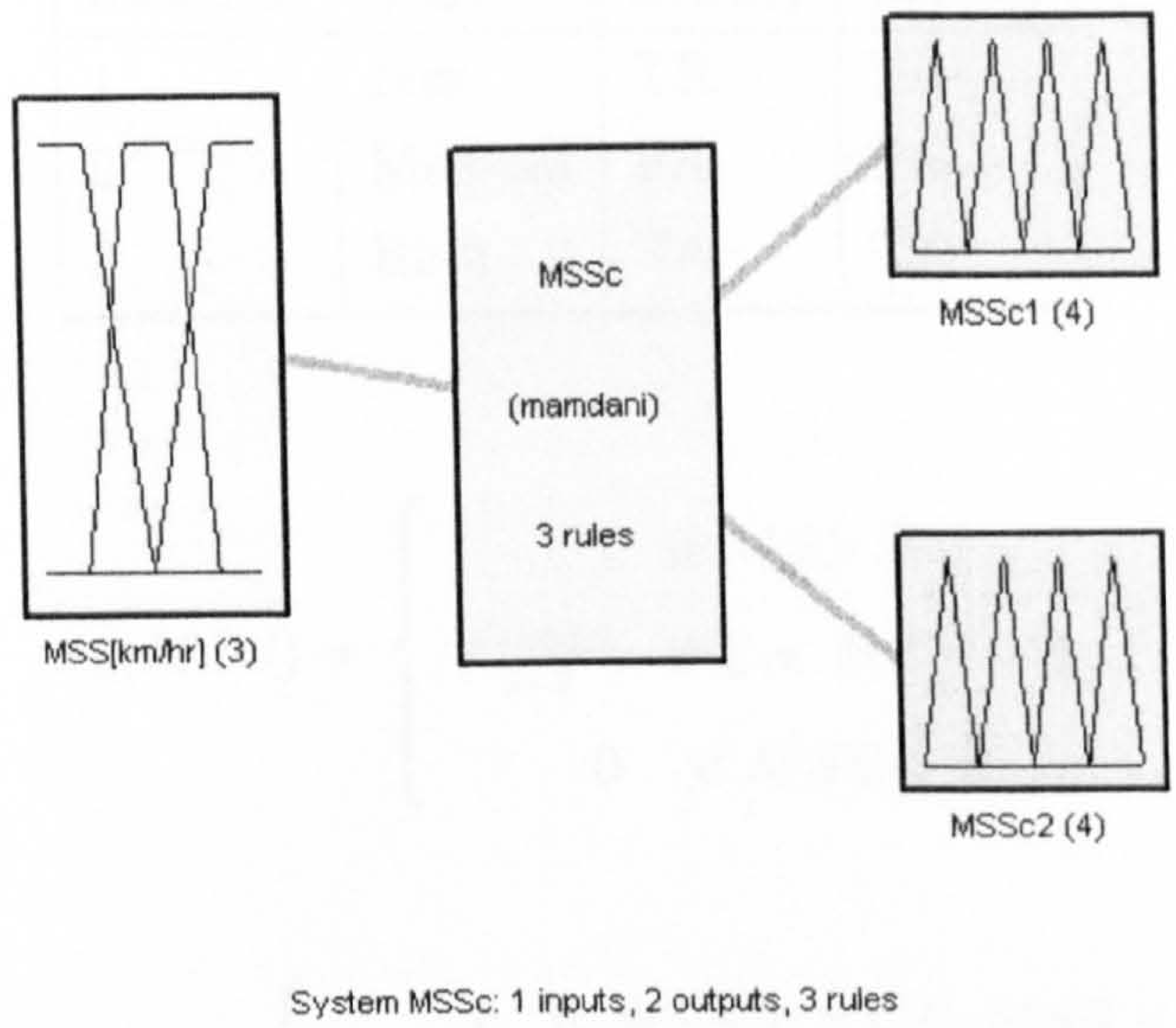

Figure 4.10: The MSS FL system

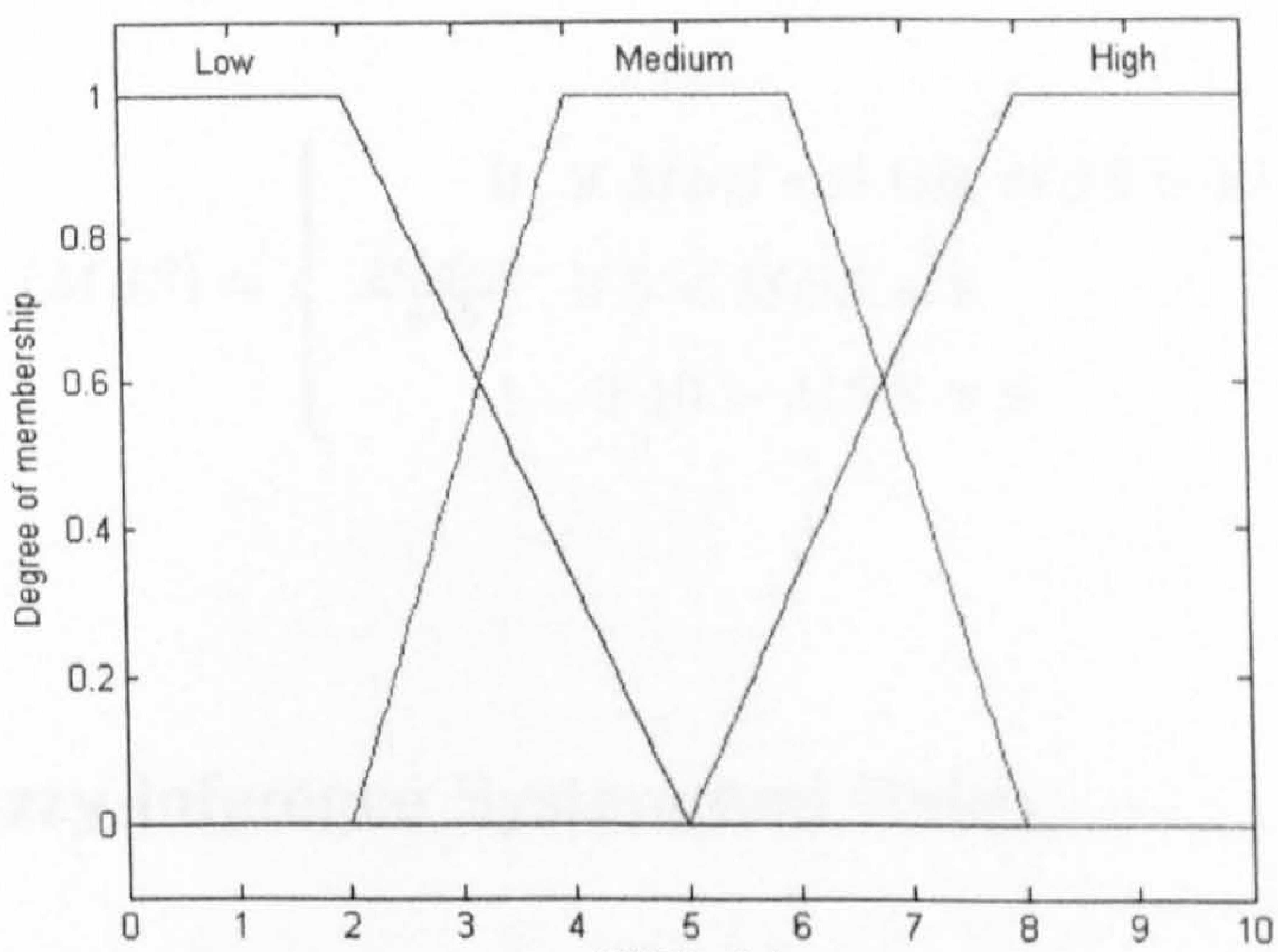

Figure 4.11: The membership functions of the input variable "MSS"

easier to implement control surface for output variables. In addition, it achieves robust inference since in the overlapped area at least two rules are usually applied.

Table 4.2: The inference rules of the MSS FL based system

Rule No.	MSS	MSS_{c1}	MSS_{c2}
1	Low	TR	TA
2	Medium	PA	PA
3	High	TA	TR

$$\alpha_L(MSS) = \begin{cases} 1 & \text{if } MSS < 2 \\ \frac{5-MSS}{5-2} & \text{if } 2 < MSS < 5 \\ 0 & \text{if } MSS > 5 \end{cases} \tag{4.7}$$

$$\alpha_M(MSS) = \begin{cases} 0 & \text{if } MSS < 2 \text{ OR } MSS > 8 \\ \frac{MSS-2}{4-2} & \text{if } 2 < MSS < 4 \\ 1 & \text{if } 6 > MSS > 4 \\ \frac{8-MSS}{8-6} & \text{if } 6 < MSS < 8 \end{cases} \tag{4.8}$$

$$\alpha_H(MSS) = \begin{cases} 0 & \text{if } MSS < 5 \text{ OR } MSS > 10 \\ \frac{MSS-5}{8-5} & \text{if } 5 < MSS < 8 \\ 1 & \text{if } 10 > MSS > 8 \end{cases} \tag{4.9}$$

4.2.3 The Fuzzy Inference System and Rules

The MSS FL based system has three simple inference rules as shown in Table 4.2. The inference rules of the MSS FL based system are designed with the aim of minimizing the handoff rate in mind and consequently utilize the networks' resources in more efficient way. The slow users are attached to the small coverage area ANs and the fast users to the larger coverage area. For example the first rule can be read as " if the mobile station speed is low then totally reject the WWAN and totally accept the WLAN".

4.2.4 The Input-Output Mapping Control Surface

Figures 4.12 and 4.13 show the control surfaces for the output variables "MSS_{c1}" and "MSS_{c2}" respectively. Figure 4.12 shows that when the mobile station speed increases, the value of "MSS_{c1}" increases smoothly. On the other hand Figure 4.13 shows that when the mobile speed increases, the value of "MSS_{c2}" decreases smoothly. These behaviours satisfy the goal of the MSS subsystem, which is avoiding the unnecessary handoff or call drop by assigning the faster user to the large-coverage area network.

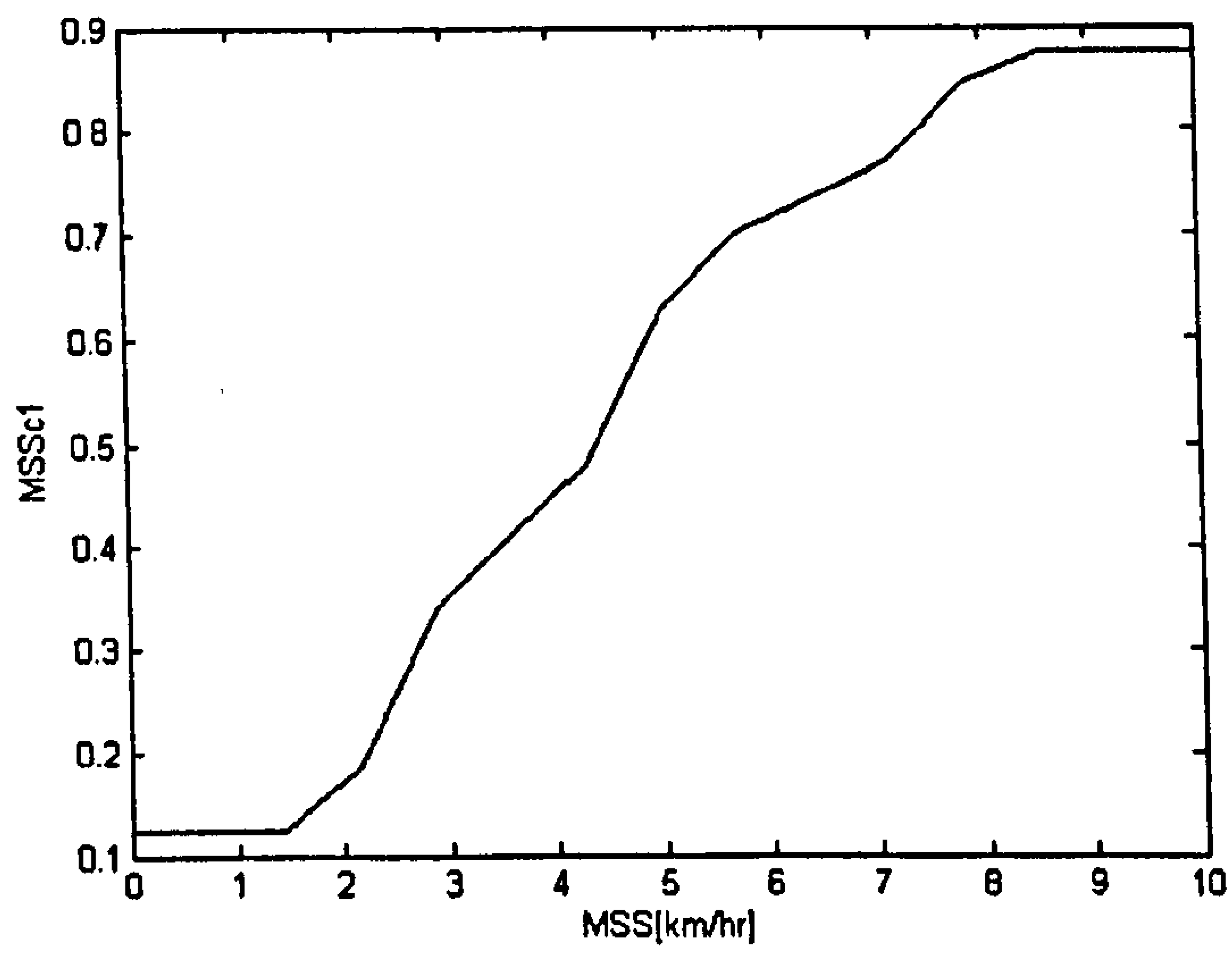

Figure 4.12: The control surface of the output variable"MSS_{c1}"

4.3 The ST FL based System

The ST FL system considers the service type criterion. ST criterion reflects the viewpoint of the application and services requirements. Figure 4.14 shows the ST FL system. The figure shows that the system has two input variables "*DelayReqc*" and "*RateReqc*" and two output variables "ST_{c1}" and "ST_{c2}".

4.3.1 The Inputs Definition

The ST system has two input variables, the first is "*DelayReqc*" to describe the end-to-end one way delay needed for the required service and the second variable is "*RateReqc*"

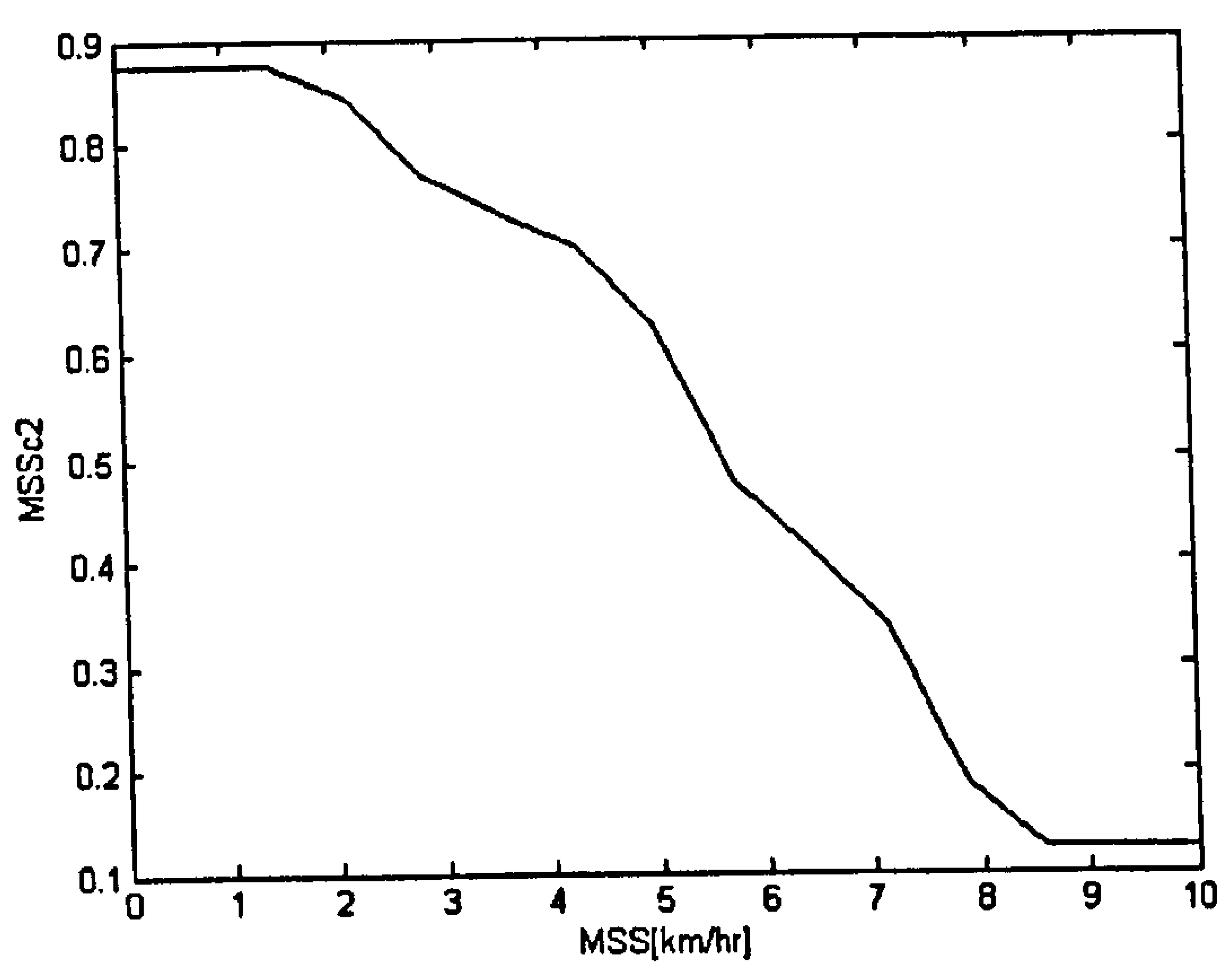

Figure 4.13: The control surface of the output variable"MSS_{c2}"

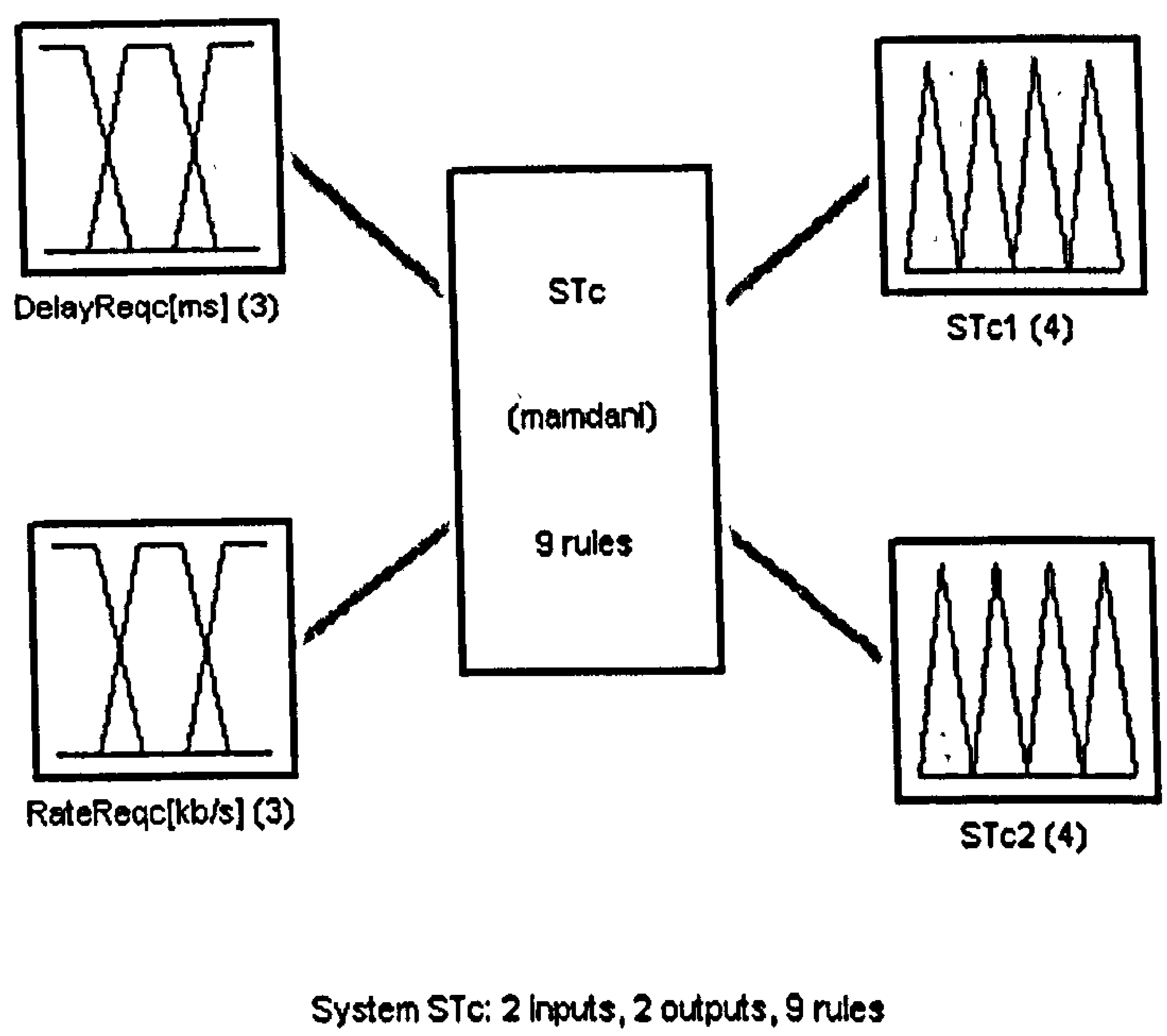

Figure 4.14: The ST FL system

to describe the bit rate needed for the required service. The universe of discourses for both input variables have been specified by considering the most sensitive service for each input variable (e.g. voice call is the most sensitive service for the delay requirements) and the least sensitive service for each input variable (e.g. non-real time data traffic is the least sensitive service for the delay requirements). Each universe is described using three linguistic variables {Low, Medium, High}. The "*DelayReqc*" universe begins with a delay between 0 and 200 ms (milliseconds), which is suitable for conventional real-time voice services and it ends with delay of more than 800 ms which is suitable for background non-real time data services. The "*RateReqc*" universe starts with a bit rate requirement less than 80 kbps, which is suitable for low bit rate services such as voice call and low bit rate video and data. It ends with a bit rate requirements of more than 320 kbps (kilo bits per second), which is suitable for high data and video traffic. Any data that comes out of the range is quantized into the nearest level.

4.3.2 The Membership Functions of the Inputs

The membership functions of the input variable "*DelayReqc*" can be described mathematically as in equations 4.10, 4.11, and 4.12. Figure 4.15 shows the membership functions of the "*DelayReqc*" variable.

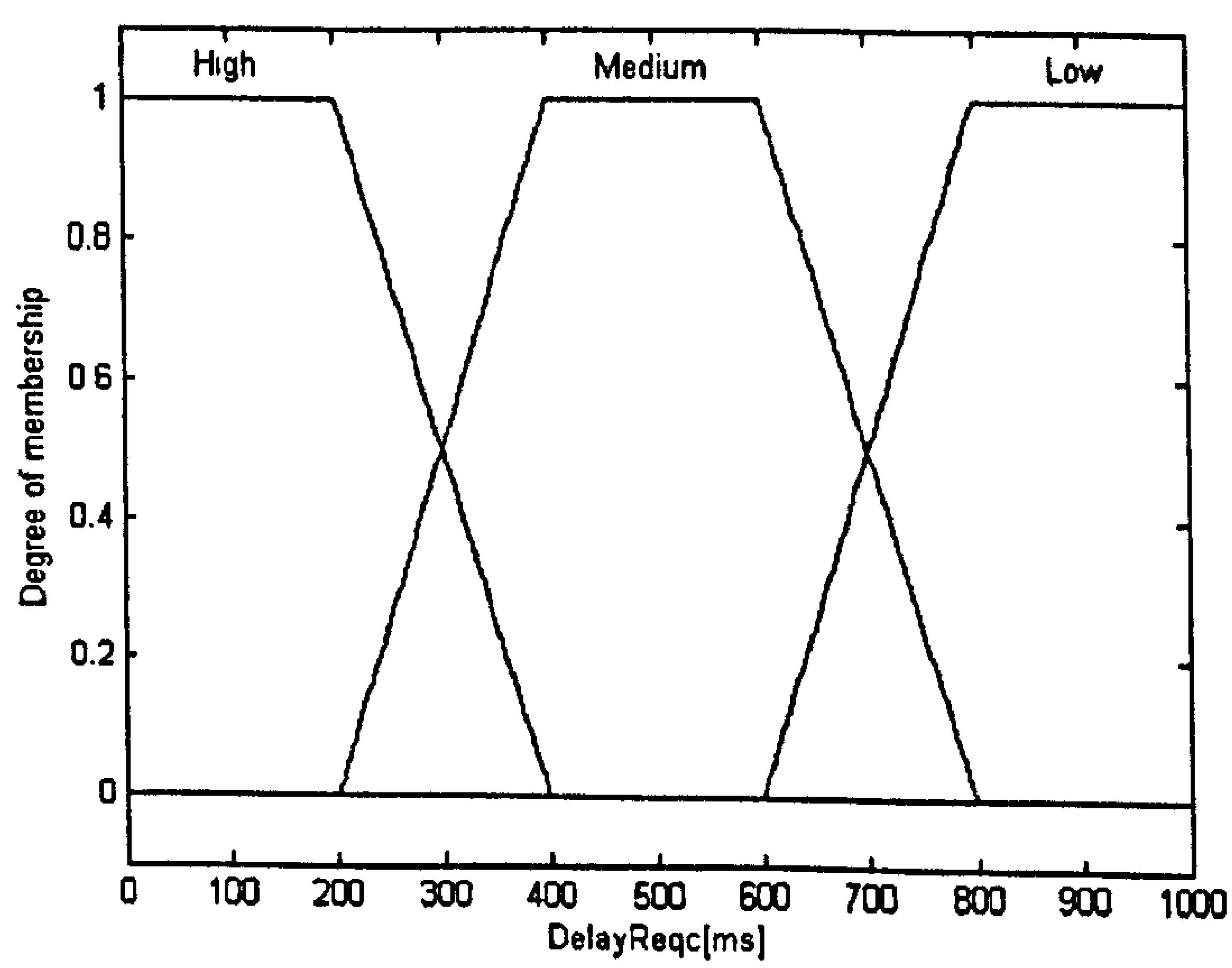

Figure 4.15: The membership functions of the input variable "*DelayReqc*"

$$\alpha_H(DelayReqc) = \begin{cases} 1 & \text{if } DelayReqc < 200 \\ \frac{400-DelayReqc}{400-200} & \text{if } 200 < DelayReqc < 400 \\ 0 & \text{if } DelayReqc > 400 \end{cases} \quad (4.10)$$

$$\alpha_M(DelayReqc) = \begin{cases} 0 & \text{if } DelayReqc < 200 \text{ OR } DelayReqc > 800 \\ \frac{DelayReqc-400}{400-200} & \text{if } 200 < DelayReqc < 400 \\ 1 & \text{if } 600 > DelayReqc > 400 \\ \frac{800-DelayReqc}{800-600} & \text{if } 600 < DelayReqc < 800 \end{cases} \quad (4.11)$$

$$\alpha_L(DelayReqc) = \begin{cases} 0 & \text{if } DelayReqc < 360 \\ \frac{DelayReqc-600}{800-600} & \text{if } 600 < DelayReqc < 800 \\ 1 & \text{if } DelayReqc > 800 \end{cases} \quad (4.12)$$

The membership functions of the input variable "'*RateReqc*" can be described mathematically as in equations 4.13, 4.14, and 4.15. Figure 4.16 shows the membership functions of the "*RateReqc*" variable.

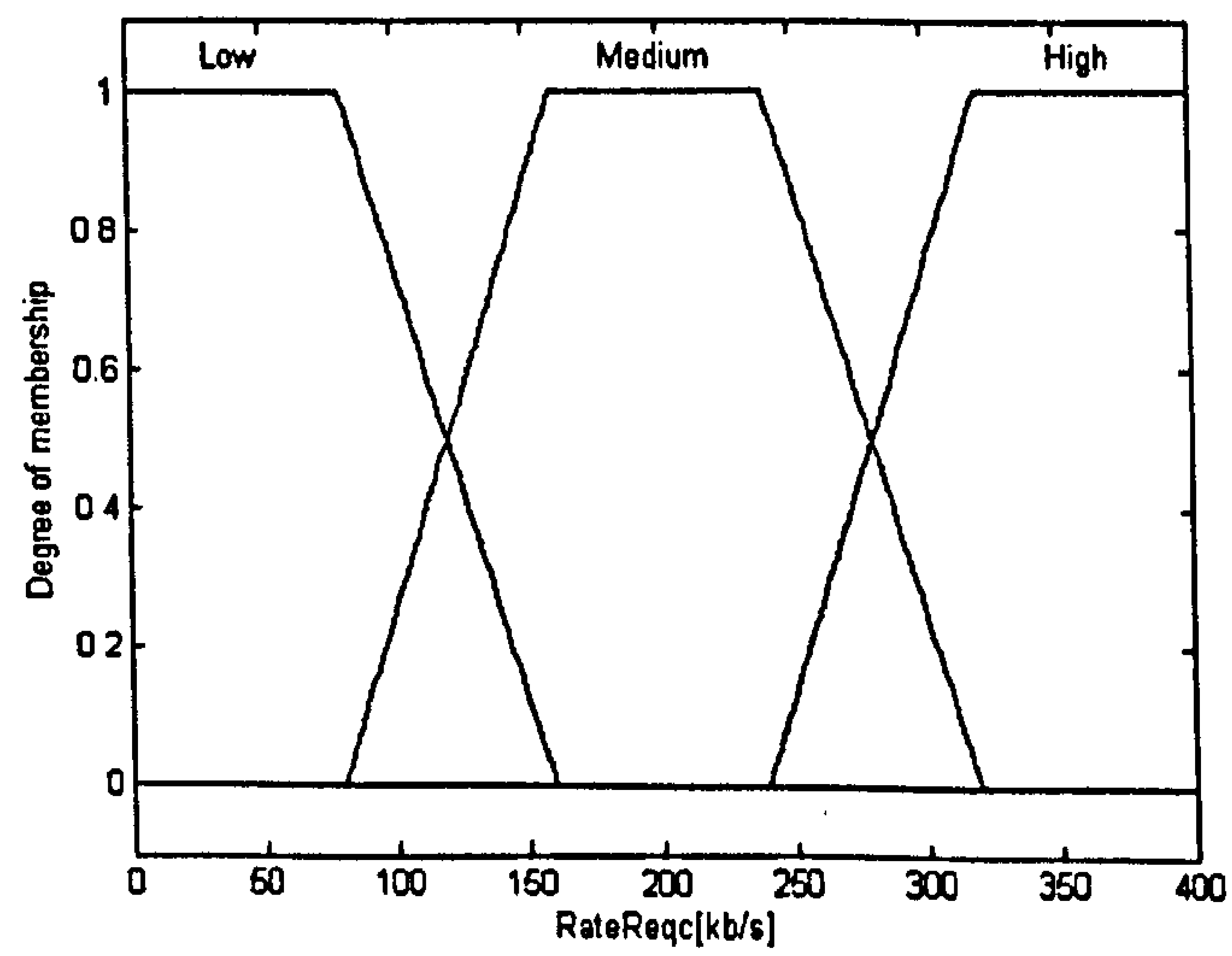

Figure 4.16: The membership functions of the input variable "*RateReqc*"

$$\alpha_L(RateReqc) = \begin{cases} 1 & \text{if } RateReqc < 80 \\ \frac{160-RateReqc}{160-80} & \text{if } 80 < RateReqc < 160 \\ 0 & \text{if } RateReqc > 160 \end{cases} \tag{4.13}$$

$$\alpha_M(RateReqc) = \begin{cases} 0 & \text{if } RateReqc < 80 \text{ OR } RateReqc > 320 \\ \frac{RateReqc-80}{160-80} & \text{if } 80 < RateReqc < 160 \\ 1 & \text{if } 240 > RateReqc > 160 \\ \frac{320-RateReqc}{320-240} & \text{if } 240 < RateReqc < 320 \end{cases} \tag{4.14}$$

$$\alpha_H(RateReqc) = \begin{cases} 0 & \text{if } RateReqc < 240 \\ \frac{RateReqc-240}{320-240} & \text{if } 240 < RateReqc < 320 \\ 1 & \text{if } RateReqc > 320 \end{cases} \tag{4.15}$$

4.3.3 The Fuzzy Inference System and Rules

The ST FL based system has nine rules as shown Table 4.3. The inference rules of the ST system are designed to assign the service requests with strict propagation delay time requirements to the WWAN networks and to assign the services request with high bit rate requirements to the WLAN network. To reflect the operators benefits, the rules can be tuned to assign more services types into the WLAN. For example, the first inference rule can be read as "If the delay requirement is high and the rate requirement is low (e.g. voice call) then totally accept the WWAN and probability reject the WLAN". Also, the ninth inference rule can be read as "If the delay requirement is low and the rate requirement is high (e.g. data traffic) then totally rejects the WWAN and totally accepts the WLAN".

4.3.4 The Input-Output Mapping Control Surface

Figures 4.17 and 4.18 show the control surfaces for the output variables "ST_{c1}" and "ST_{c2}" respectively. Figure 4.17 shows that by decreasing the value of "*DelayReqc*" or the value of "*RateReqc*", the chance of selecting the WWAN network increases (i.e.

"ST_{c1}" increases). If both variables are decreasing together, the chance of selecting the WWAN network becomes higher. On the other hand, Figure 4.18 shows that by increasing the value of "*DelayReqc*" or the value of "*RateReqc*", the chance of selecting the WLAN network increases (i.e. "ST_{c2}" increases). If both input variables are increasing together, the chance of selecting the WLAN network becomes higher.

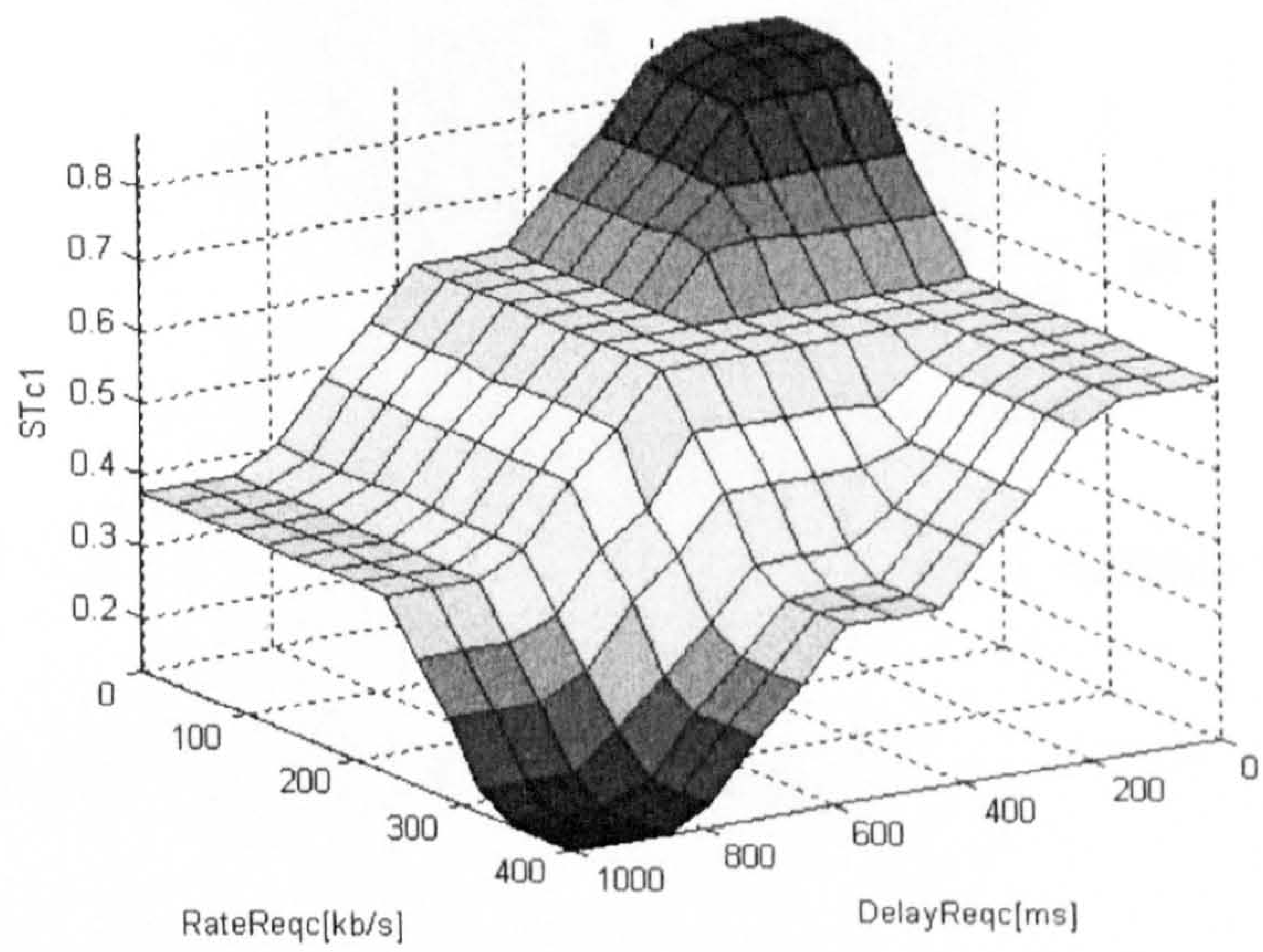

Figure 4.17: The control surface of the output variable "ST_{c1}"

Table 4.3: The inference rules of the ST FL based system

Rule No.	*DelayReqc*	*RateReqc*	ST_{c1}	ST_{c2}
1	High	Low	TA	PR
2	High	Medium	PA	PR
3	High	High	PA	PA
4	Medium	Low	PA	PR
5	Medium	Medium	PA	PA
6	Medium	High	PR	PA
7	Low	Low	PR	TA
8	Low	Medium	PR	TA
9	Low	High	TR	TA

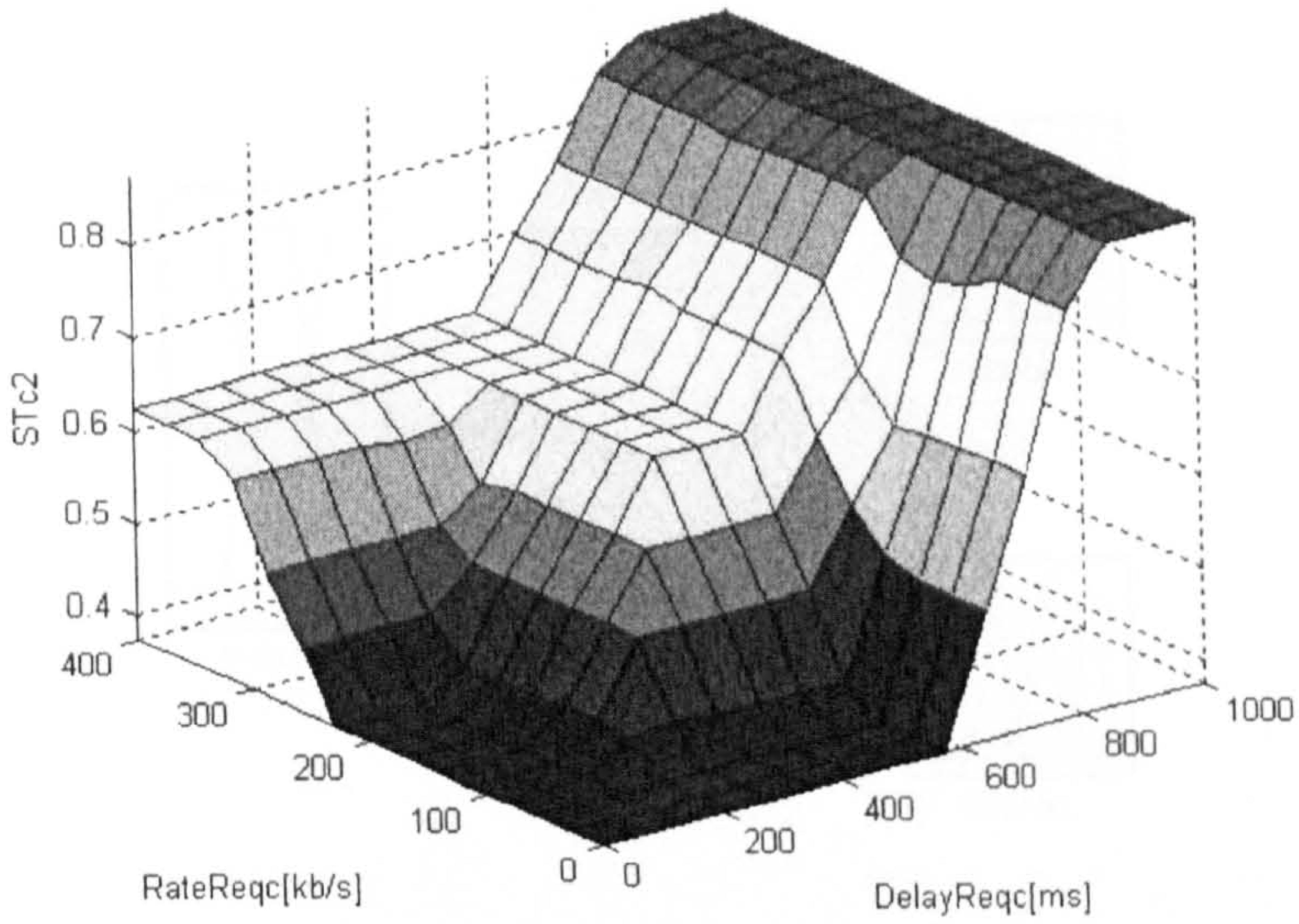

Figure 4.18: The control surface of the output variable "ST_{c2}"

4.4 The PRc FL based System

The PRc system considers the user preferred price (i.e. PRICE) criterion. PRICE criterion reflects the user viewpoint because the users may prefer to select one network among others due to its low price or their previous satisfaction. Figure 4.19 shows the PRc FL system. The figure shows that the system has one input variable "*Price*" and two output variables "PR_{c1}" and "PR_{c2}".

4.4.1 The Inputs Definition

The PRc system has only one input variable "*Price*" to describe the user preferred price. The universe of discourse scales the "*Price*" variable into ten degrees between 0 and 10. A higher degree represents a higher price that could be paid by user. Three linguistic variables have been used to describe the universe of discourse {Low, Medium, and High}. The linguistic variable "Low" indicates a low price preferred by the user, the variable "Medium" indicates that the user prefers a medium price, and the variable "High" indicates that the user can pay a high price.

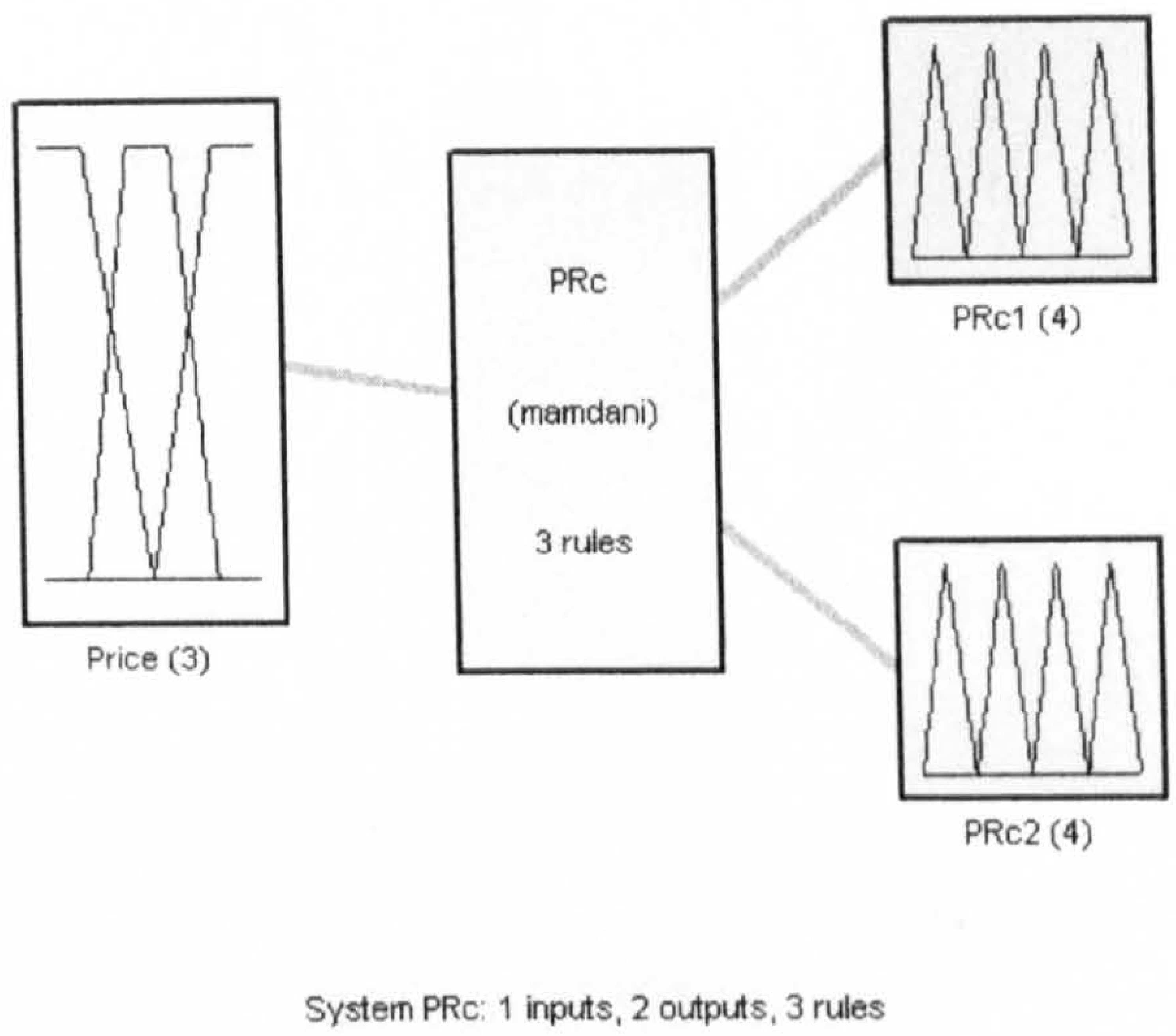

Figure 4.19: The PRc FL system

4.4.2 The Membership Functions of the Inputs

The membership functions of the input variable "*Price*" can be described mathematically as in equations 4.16, 4.17, and 4.18. Figure 4.20 shows the membership functions of the "*Price*" variable. The significant overlapping between the first and second membership functions and between the second and third membership functions imply smoother and easier to implement control surface for both output variables. In addition, it achieves robust inference since in the overlapped area at least two rules are usually applied.

$$\alpha_L(Price) = \begin{cases} 1 & \text{if } Price < 2 \\ \frac{5-Price}{5-2} & \text{if } 2 < Price < 5 \\ 0 & \text{if } Price > 5 \end{cases} \tag{4.16}$$

$$\alpha_M(Price) = \begin{cases} 0 & \text{if } Price < 2 \text{ OR } Price > 8 \\ \frac{Price-4}{4-2} & \text{if } 2 < Price < 4 \\ 1 & \text{if } 8 > Price > 6 \\ \frac{8-Price}{8-6} & \text{if } 6 < Price < 8 \end{cases} \tag{4.17}$$

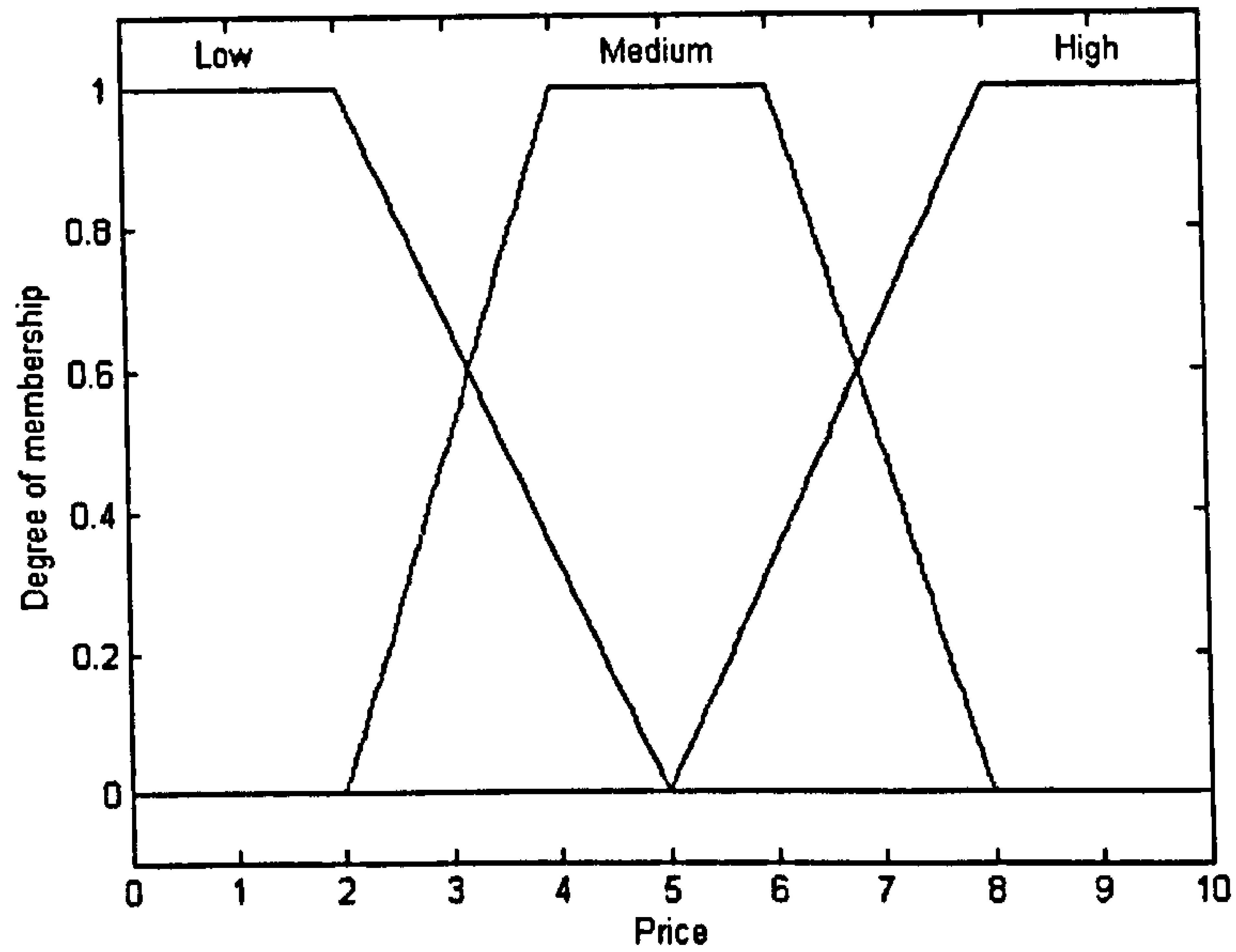

Figure 4.20: The membership functions of "*Price*" input variable

$$\alpha_H(Price) = \begin{cases} 0 & \text{if } Price < 5 \\ \frac{Price-5}{8-5} & \text{if } 5 < Price < 8 \\ 1 & \text{if } Price > 8 \end{cases} \tag{4.18}$$

4.4.3 The Fuzzy Inference System and Rules

Table 4.4 shows the three inference rule of the PRc FL based system. The PRc FL control system inference rules are designed so that the users with a low price target are assigned to the WLAN because of its lower cost. The users with a high price target (and of course better QoS) are assigned to WWAN, which usually costs more. For example, the first inference rule can be read as "If the user target price is low then totally rejects the WWAN and totally accepts the WLAN".

4.4.4 The Input-Output Mapping Control Surface

Figures 4.21 and 4.22 show the control surfaces for the output variables "PR_{c1}" and "PR_{c2}" respectively. Figures 4.21 and 4.22 show that when the user can pay more (i.e. higher "*Price*" variable value), the chance of the user to be assigned to the WWAN is

Table 4.4: The inference rules of the PRc FL based system

Rule No.	*Price*	PR_{c1}	PR_{c2}
1	Low	TR	TA
2	Medium	PA	PA
3	High	TA	TR

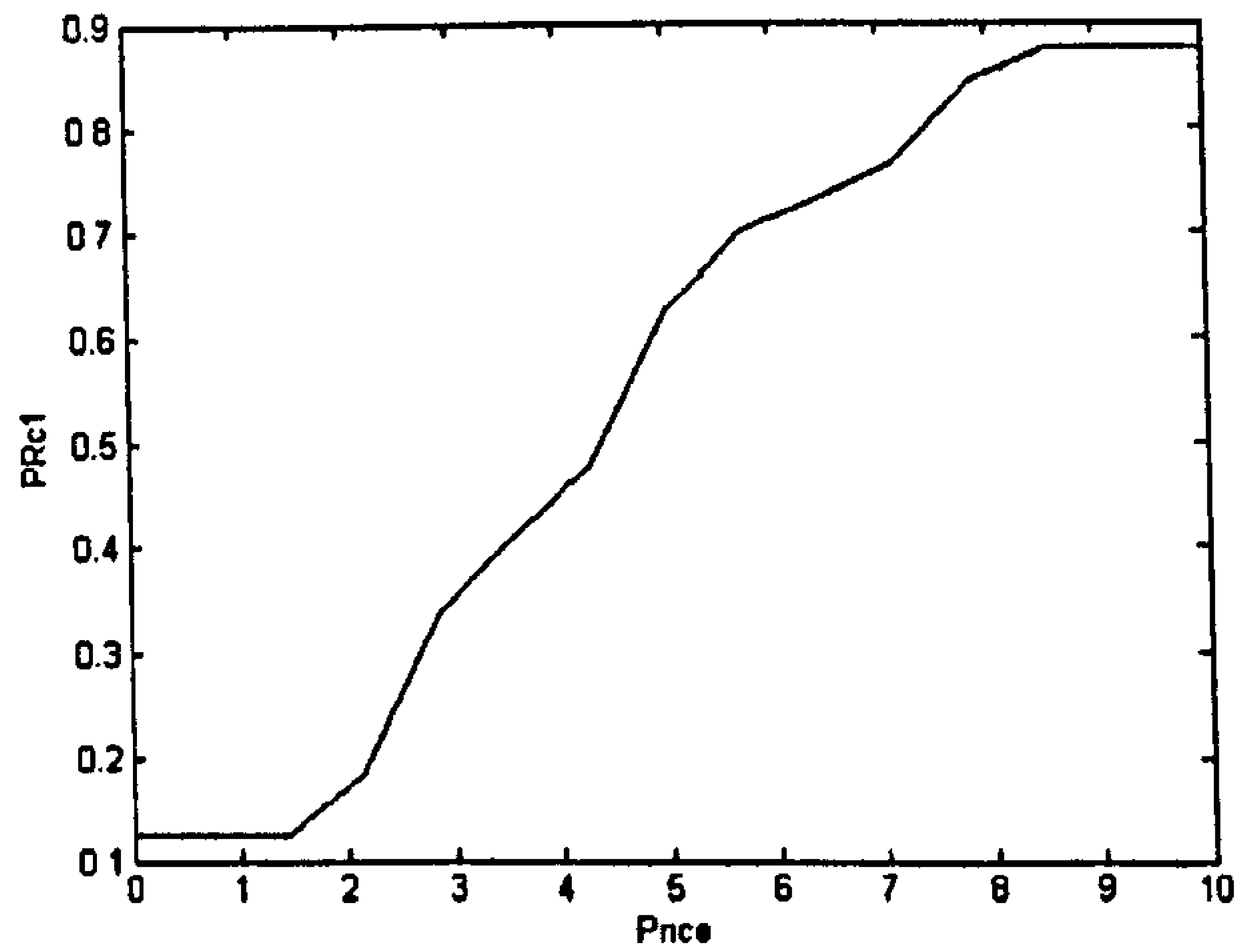

Figure 4.21: The control surface of the output variable "PR_{c1}"

becoming higher (i.e. "PR_{c1}" increases) and the chance of the user being assigned to the WLAN is becoming lower (i.e. "PR_{c2}" decreases). On the other hand when the user can pay less (i.e. lower "*Price*" variable value), the chance of the user being assigned to the WWAN is becoming lower (i.e. "PR_{c1}" decreases) and the chance of the user being assigned to the WLAN is becoming lower (i.e. "PR_{c2}" increases). These behaviours reflect the requirements of the PRc FL systems, where the operator needs to assign the less important users to the lower cost network and the more important users to the higher cost network.

4.5 The Output of the FL based Systems and the Defuzzification Process

Every FL system has two output variables, one variable to describe the probability of acceptance for the new user in the WWAN network (i.e. the first network) and the

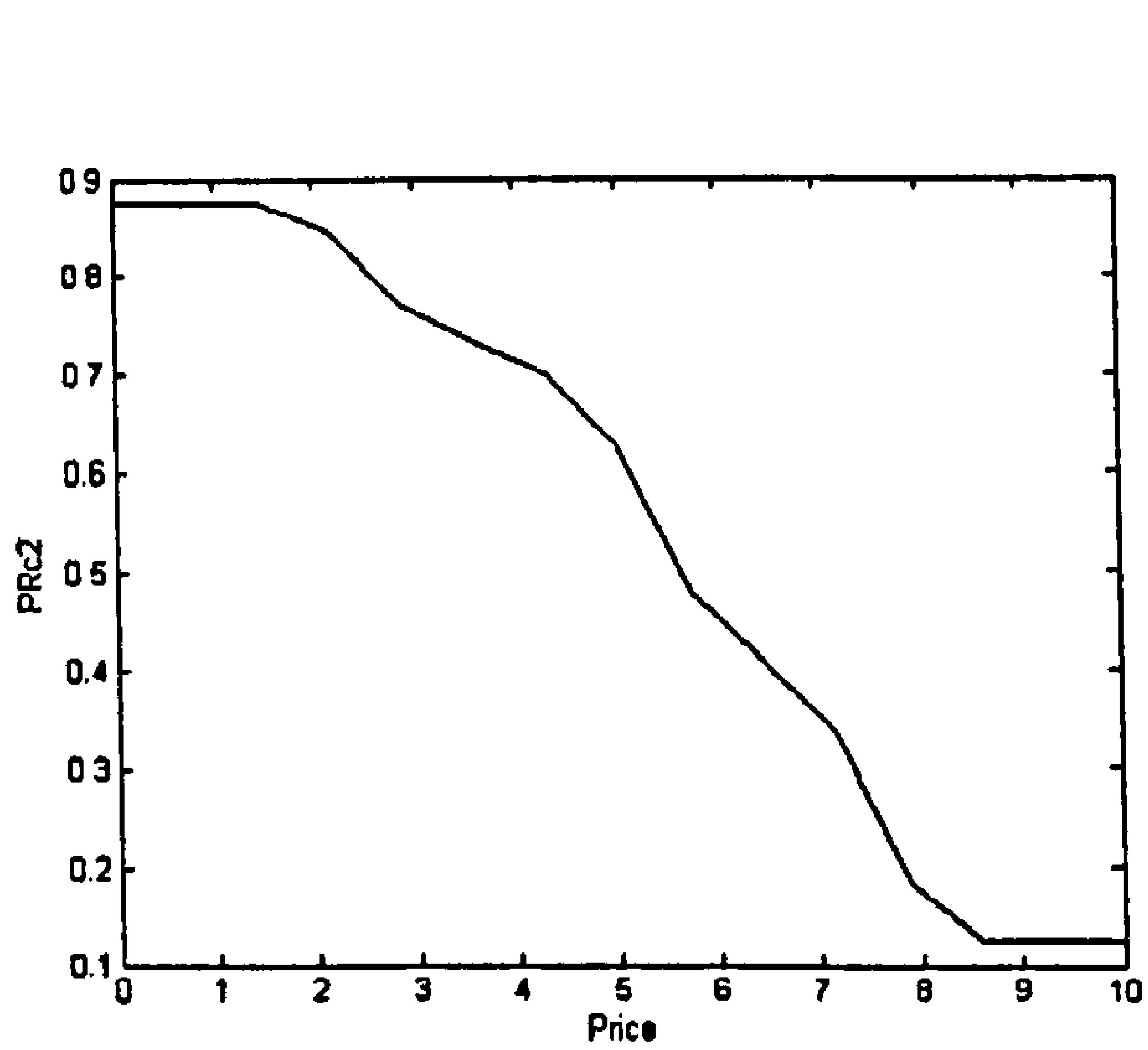

Figure 4.22: The control surface of the output variable "PR_{c2}"

other variable to describe the probability of acceptance for the new user in the WLAN network (i.e. the second network). Each output variable has four membership functions TR (Totally Reject), PR (Probability Reject), PA (Probability Accept), and TA (Totally Accept). The systems output variables are "RSS_{c1}" and "RSS_{c2}" for the RSS system, "MSS_{c1}" and "MSS_{c2}" for the MSS system, "ST_{c1}" and "ST_{c2}" for the ST system, and "PR_{c1}" and "PR_{c2}" for the PRc system. Figure 4.23 shows the "MSS_{c2}" variable with its membership functions as a sample for the output variables. Equations 4.19, 4.20, 4.21 and 4.22 describe the membership functions of the "MSS_{c2}" system.

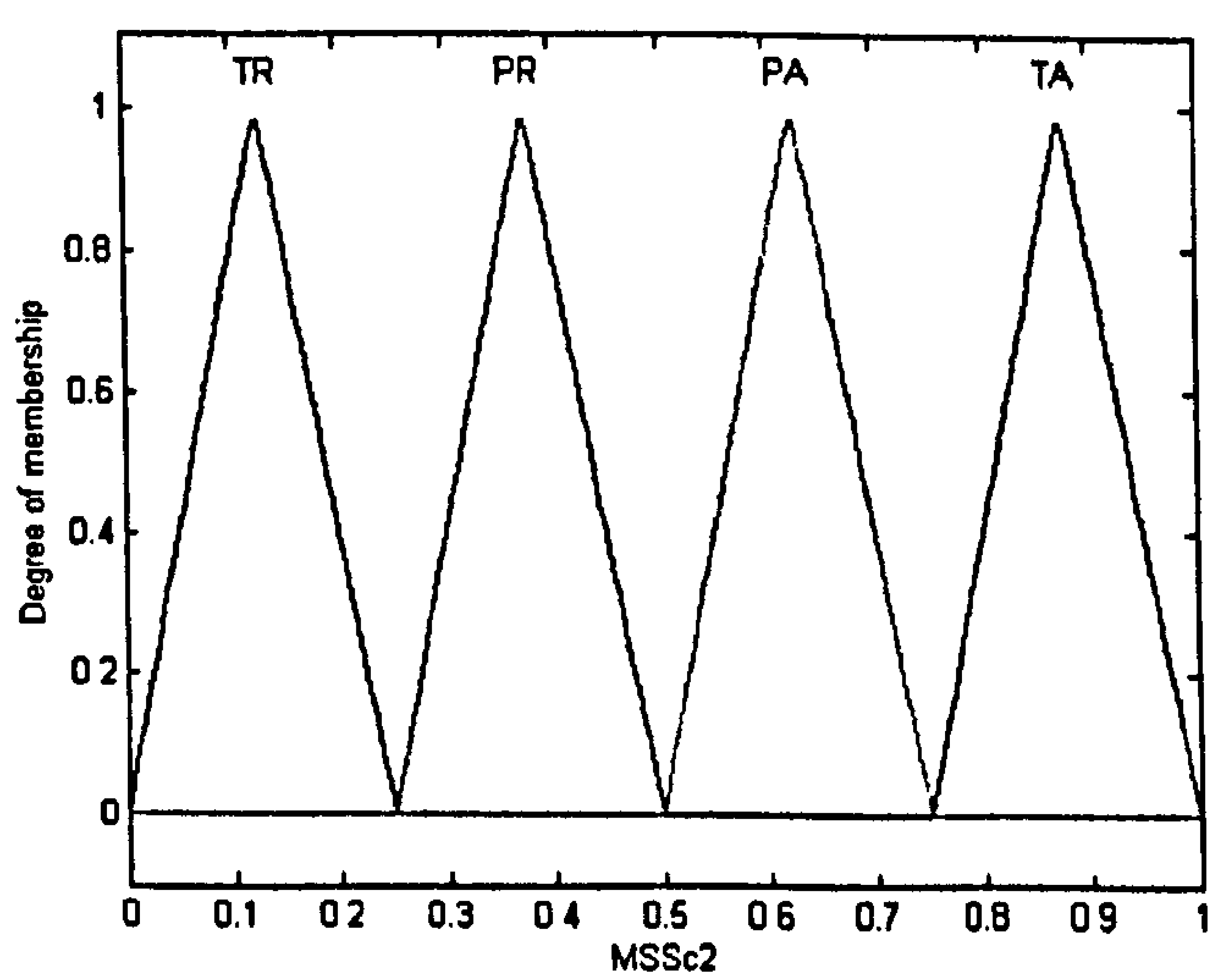

Figure 4.23: The membership functions of the output variable "MSS_{c2}"

$$\alpha_{TR}(MSSc2) = \begin{cases} 0 & \text{if } MSSc2 < 0 \text{ OR } MSSc2 > 0.25 \\ \frac{MSSc2-0}{0.125-0} & \text{if } 0 < MSSc2 < 0.125 \\ \frac{0.25-MSSc2}{0.25-0.125} & \text{if } 0.125 < MSSc2 < 0.25 \end{cases} \tag{4.19}$$

$$\alpha_{PR}(MSSc2) = \begin{cases} 0 & \text{if } MSSc2 < 0.25 \text{ OR } MSSc2 > 0.6 \\ \frac{MSSc2-0.25}{0.375-0.25} & \text{if } 0.25 < MSSc2 < 0.375 \\ \frac{0.5-MSSc2}{0.5-0.375} & \text{if } 0.375 < MSSc2 < 0.5 \end{cases} \tag{4.20}$$

$$\alpha_{PA}(MSSc2) = \begin{cases} 0 & \text{if } MSSc2 < 0.5 \text{ OR } MSSc2 > 0.75 \\ \frac{MSSc2-0.5}{0.625-0.5} & \text{if } 0.5 < MSSc2 < 0.625 \\ \frac{0.75-MSSc2}{0.75-0.625} & \text{if } 0.625 < MSSc2 < 0.75 \end{cases} \tag{4.21}$$

$$\alpha_{TA}(MSSc2) = \begin{cases} 0 & \text{if } MSSc2 < 0.75 \text{ OR } MSSc2 > 1.0 \\ \frac{MSSc2-0.75}{0.875-0.75} & \text{if } 0.75 < MSSc2 < 0.875 \\ \frac{1.0-MSSc2}{1.0-0.875} & \text{if } 0.875 < MSSc2 < 1.0 \end{cases} \tag{4.22}$$

Five important defuzzification methods are used extensively in the design of FL based systems. These methods are the Centroid of Area (CoA), Bisector of Area (BoA), Mean of Maximum (MOM), Smallest of Maximum (SOM), and Largest of Maximum (LOM). Figure 4.24 shows the five methods.

The CoA method has been used in our study because it has several advantages over the other methods. These advantages include a) it is the most accurate method, b) it is the most widely used, c) it does not disregard the shape of the fuzzy set as the Maximum methods, and d) it does not suffer from ambiguity and can work in any situation because it usually has a defined state.

The main disadvantage of the CoA method is the high computational complexity. The computational complexity of this method is reduced using the simple used output membership functions. The CoA defuzzification technique can be expressed as in equation 4.23.

$$X_{Centroid} = \frac{\int_a^b x * \alpha_x \, dx}{\int_a^b \alpha_x \, dx} \tag{4.23}$$

4.6 The MCDM Component

The MCDM system has to rank the considered alternatives according to their attractiveness. The MCDM system aims to a) achieve the highest number for satisfied users, b) achieve the highest number of users who get better quality, and c) save the resources of high cost networks by increasing the usage of low cost network. Two alternatives are considered by the MCDM, the first one is a WWAN network and the second one is a WLAN network.

The input criteria of the MCDM are the MSS, RSS, ST, and PRICE. The SMART decision making tool described on subsection 2.5.2 is used. The SMART employs a relatively uncomplicated and straightforward manipulation method, which makes it stronger and easier to use in a hybrid and more complex models such as the developed one in this study. With the aid of both FL and GA, SMART has all the capabilities required to address the specific considerations that are involved in the ANS decision making process. SMART can be quickly and easily understood by inexperienced decision makers. However, to get better understanding and deeper insights into the selection decision making, other advanced MCDM method has been used in the next chapter.

The alternatives performance scores against criteria are read from the outputs of the

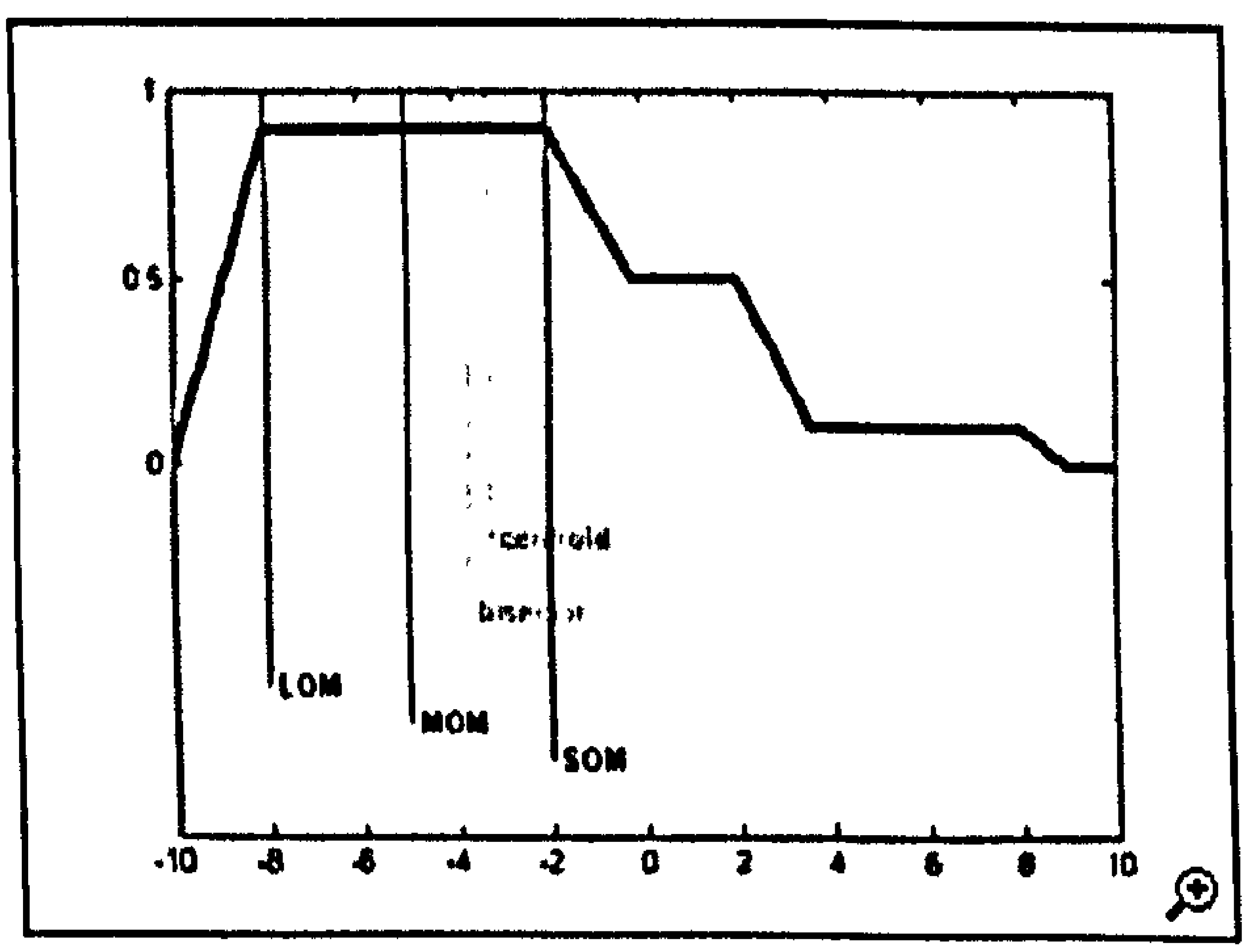

Figure 4.24: The main defuzzification methods

parallel FL systems in the first component (i.e. "RSS_{c1}, "RSS_{c2}, "MSS_{c1}, "MSS_{c2}, "ST_{c1}, "ST_{c2}, "PR_{c1}, and "PR_{c2}). It is worth noting that, since all the outputs of the FL systems are in the range [0, 1], there is not any need to scale the scores of the alternatives against the criteria, which is a big enhancement over the traditional SMART tool. Equation 4.24 shows the alternatives performance scores matrix "$Alts$" for the MCDM.

$$Alts = \begin{pmatrix} RSS_{c1} & RSS_{c2} \\ MSS_{c1} & MSS_{c2} \\ PR_{c1} & PR_{c2} \\ ST_{c1} & ST_{c2} \end{pmatrix} \tag{4.24}$$

The criteria weights matrix CW is shown in equation 4.25.

$$CW = \begin{pmatrix} W_s & W_v & W_t & W_u \end{pmatrix} \tag{4.25}$$

W_s is the assigned weight for the RSS criterion, W_v is the assigned weight for the MSS criterion, W_t is the assigned weight for the ST criterion, and W_u is the assigned weight for the PRICE criterion. The criteria weights can be real or integer numbers. For real-value weights, it should be between [0,1] and it could be subject to the constraint stated in equation 4.26.

$$W_s + W_v + W_t + W_u = 1 \tag{4.26}$$

For integer-value weights, it should be between [0,100] and it could be subject to the constraint stated in equation 4.27.

$$W_s + W_v + W_t + W_u = 100. \tag{4.27}$$

The weights can be assigned manually according to the experience of the decision makers about the importance of each criterion. The weights also can be assigned using an optimization method. Both method have been used and compared in our study.

The ranking value (i.e. the total score) of WWAN network X_{WAN} and the ranking value of WLAN network X_{LAN} are calculated according to equations 4.28 and 4.29

respectively.

$$X_{WAN} = \frac{RSS_{c1} * W_s + MSS_{c1} * W_v + ST_{c1} * W_t + PR_{c1} * W_u}{TW} \tag{4.28}$$

$$X_{LAN} = \frac{RSS_{c2} * W_s + MSS_{c2} * W_v + ST_{c2} * W_t + PR_{c2} * W_u}{TW} \tag{4.29}$$

where TW is the total weight and is calculated using equation 4.30.

$$TW = W_v + W_s + W_t + W_u \tag{4.30}$$

4.7 Illustrative Numerical Examples

This section illustrates the developed operator ANS algorithm by giving some numerical examples for real cases. Let's assume three users {user "A", user "B", and user "C"}. User "A" has a mobile terminal that has two radio interfaces for both UMTS and IEEE802.11g WLAN networks. While "A" is walking at a speed of 5 km/hr, he is trying to access the Internet to check his email. User "A" prefers to get the services at as low a price as possible. The measured received signals from UMTS and WLAN are -91 and -78 dBm respectively. User "B" has a laptop with suitable interfaces for IEEE 802.16 WiMAX and IEEE802.11g WLAN. While "B" is sitting in his house, he is trying to watch some online TV channels through the Internet. The measured received signals from WiMAX and WLAN are -80 and -85 dBm respectively. User "C" is running at a speed of 11 km/hr, while he is trying to make a voice call using his mobile terminal that could support both cdmaOne (i.e. IS-95a) and GSM networks. User "C" is on a macro cdmeOne cell and a micro GSM cell. The measured received signals from cdmaOne and GSM networks at the mobile terminal interface are -83 and -82 dBm respectively. Both users "B" and "C" are waiting for the best quality available at any price.

The first step is the pre-processing stage (i.e. ANS initiation phase), where the suitable information required for the decision is gathered from the different sources to be available at the CRRM entity, where the OSA resides. The "RSS_1" and "RSS_2" values are measured at the mobile station interfaces and are sent to the CRRM entity (i.e. mobile-assisted network-controlled mode). In fact, the direct measured values for "RSS_1" and "RSS_2" are not used and an average value for "RSS_1" and "RSS_2" during a specific period of time is used instead of that. The "MSS" value is measured

Table 4.5: The collected Information from the pre-processing step

Variables	user "A"	user "B"	user "C"
RSS_1	-91 dBm	-80 dBm	-83 dBm
RSS_2	-78 dBm	-85 dBm	-82 dBm
MSS	5km/hr	0km/hr	11km/hr
$Price$	3	7	8
$DelayReqc$	800ms	400ms	200ms
$RateReqc$	64kbps	400kbps	12.2kbps

at the CRRM entity or mobile station using some mobile speed estimation methods. User "C" moves at a speed higher than the maximum value in the "MSS" universe of discourse, so it is quantized into the most correct value (i.e. 10km/hr). The delay and rate requirements' values depend on the type of the required service. In fact, these values depend on the service models adopted by the different QoS standards for the different types of networks. If a non-adaptive service model is used, user "A" requests email service, which is low bit rate with low delay propagation requirements (e.g. 64 kbps and 800 ms respectively). The user "B" requests online TV through the Internet, which is high bit rate and medium propagation delay services (e.g. more than 400 kbps and around 400 ms). The user "C" requests voice call service, which is low bit rate and strict delay requirements (e.g. 12.2 kbps and 200 ms respectively). The user can specify his/her preferred price using a ten-degrees scale in his/her mobile station and send it to the CRRM entity or it can be retrieved from a pre-existing database in the CRRM entity. Users "A", "B" and "C" "$Price$" values are assumed to be 3, 7 and 8 respectively. Table 4.5 summarizes the collected information and measurements in the pre-processing step.

The second step is applying the collected information into the FL parallel systems inputs to get the initial preference score for each alternative with respect to each criterion. Figure 4.25 shows the values of both "RSS_{c1}" and "RSS_{c2}" for user "A". The figure shows that the values of both "RSS_{c1}" and "RSS_{c2}" are 0.625 and 0.625 respectively. By applying the values of the "RSS_1" and "RSS_2" for user "B" and user "C", we have got 0.875 and 0.625 for user "B" and 0.733 and 0.625 for user "C" "RSS_{c1}" and "RSS_{c2}" values.

Figure 4.26 shows the values of both "MSS_{c1}" and "MSS_{c2}" for user "A". The figure

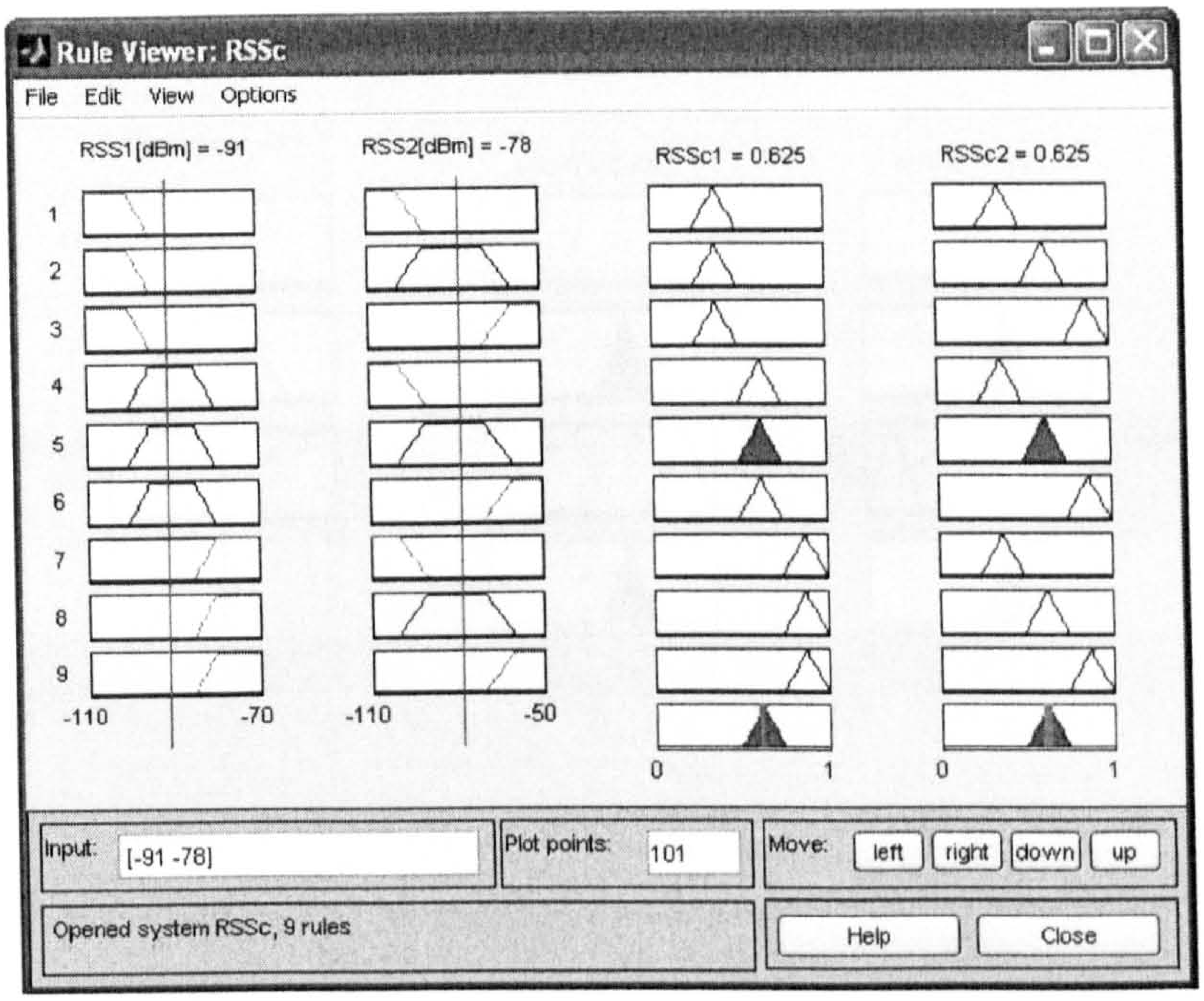

Figure 4.25: "RSS_{c1}" and "RSS_{c2}" values for user "A"

shows that the values of both "MSS_{c1}" and "MSS_{c2}" are 0.625 and 0.625 respectively. By applying the value of the "MSS" for user "B" and user "C", we have got 0.125 and 0.875 for user "B" and 0.875 and 0.125 for user "C" "MSS_{c1}" and "MSS_{c2}" values.

Figure 4.27 shows the values of both "ST_{c1}" and "ST_{c2}" for user "A". The figure shows that the values of both "ST_{c1}" and "ST_{c2}" are 0.375 and 0.875 respectively. By applying the value of the input variables for user "B" and user "C", we have got 0.375 and 0.625 for user "B" and 0.875 and 0.375 for user "C" "ST_{c1}" and "ST_{c2}" values.

Figure 4.28 shows the values of both "PR_{c1}" and "PR_{c2}" for user "A". The figure shows that the values of both "PR_{c1}" and "PR_{c2}" are 0.354 and 0.761 respectively. By applying the value of the input variable for user "B" and user "C", we have got 0.761 and 0.354 for user "B" and 0.875 and 0.125 for user "C" "PR_{c1}" and "PR_{c2}" values.

The total ranking values for both networks are calculated according to equations 4.28 and 4.29. If all criteria have the same importance, then $W_v = W_s = W_t = W_u = 1$. For user "A" $X_{WAN} = 0.495$ and $X_{LAN} = 0.7215$ .For user "B" $X_{WAN} = 0.43225$ and $X_{LAN} = 0.62$. For user "C" $X_{WAN} = 0.84$ and $X_{LAN} = 0.3125$. Based on the ranking values, the most attractive network is selected for each user.

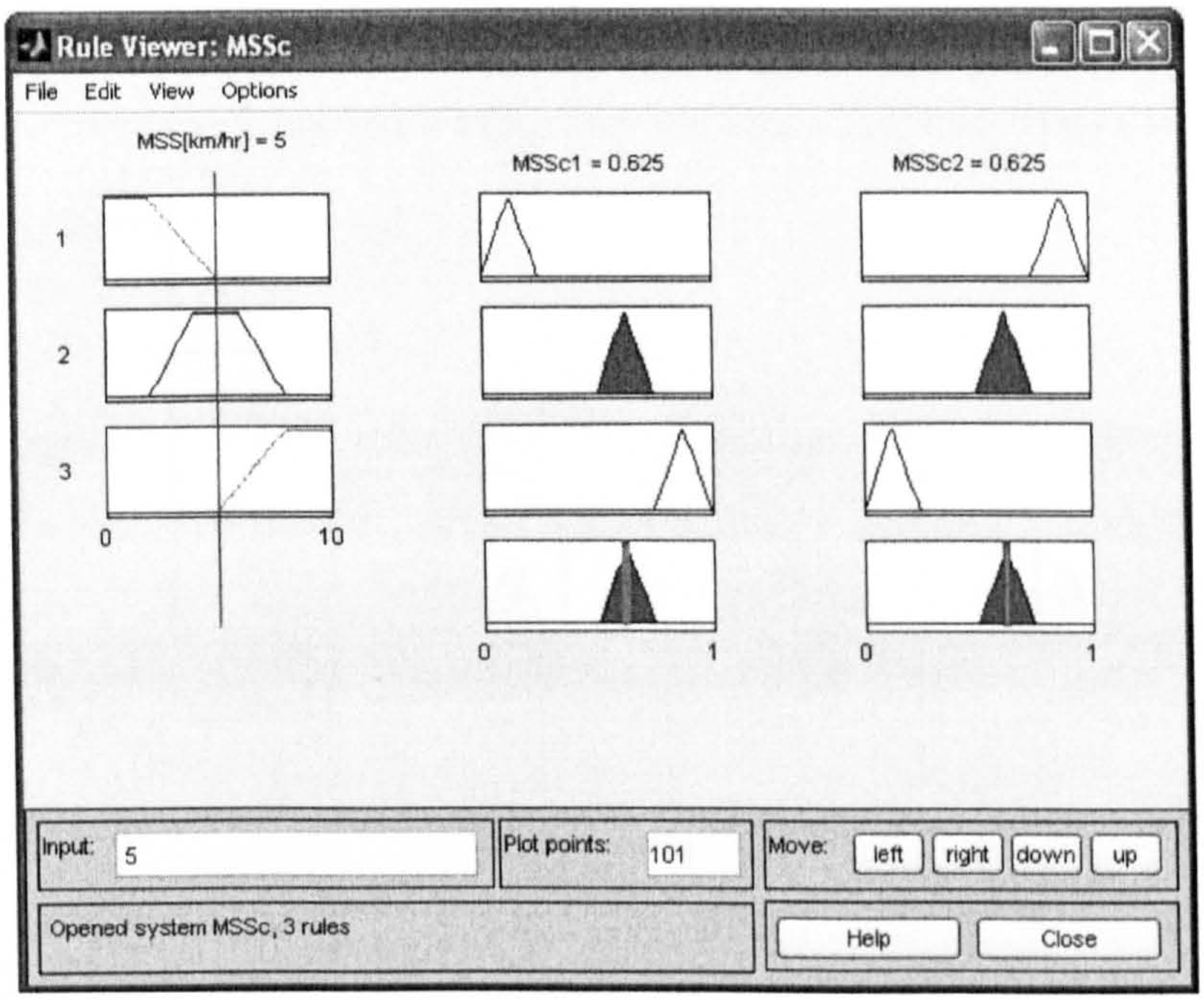

Figure 4.26: "MSS_{c1}" and "MSS_{c2}" values for user "A"

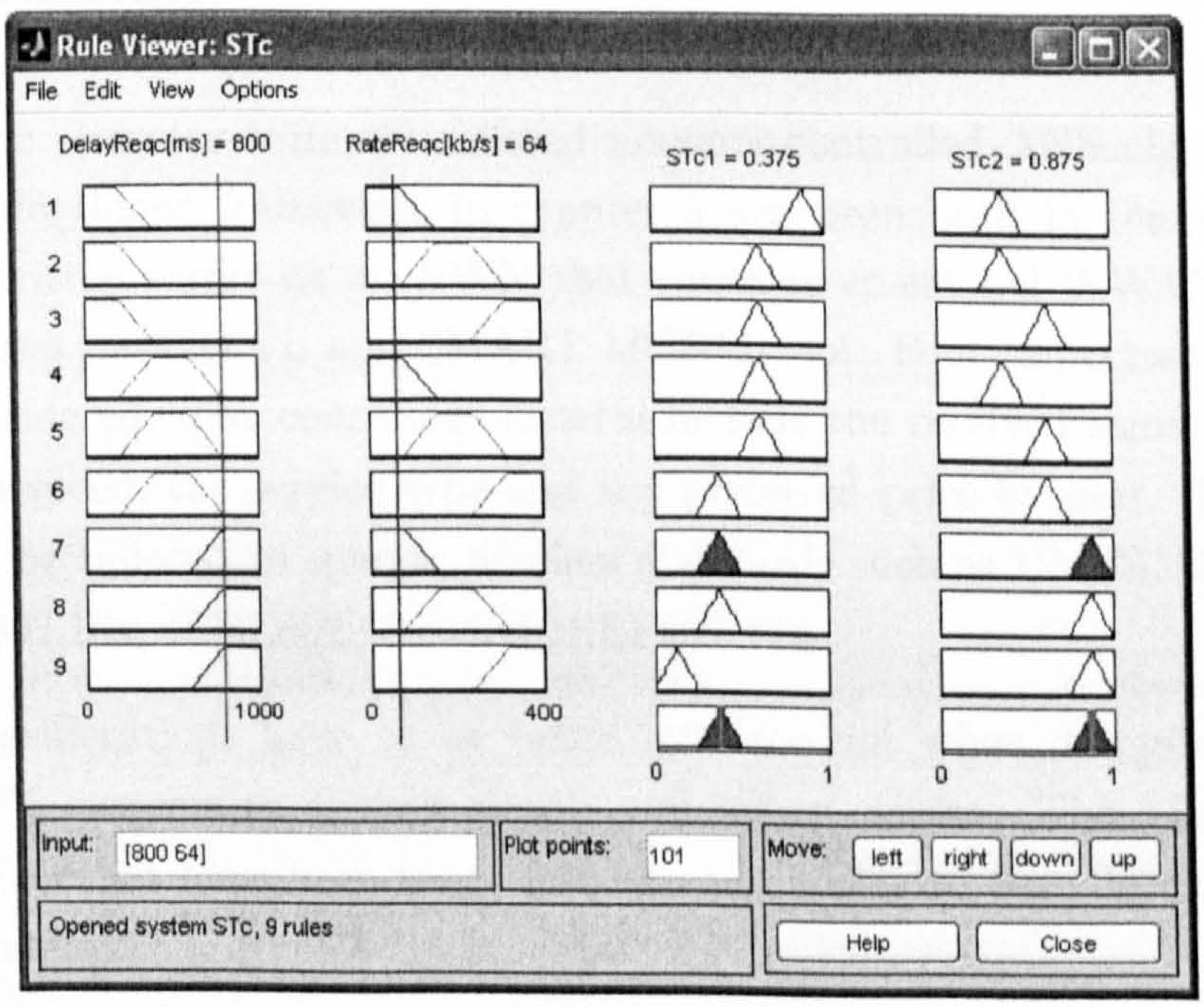

Figure 4.27: "ST_{c1}" and "ST_{c2}" values for user "A"

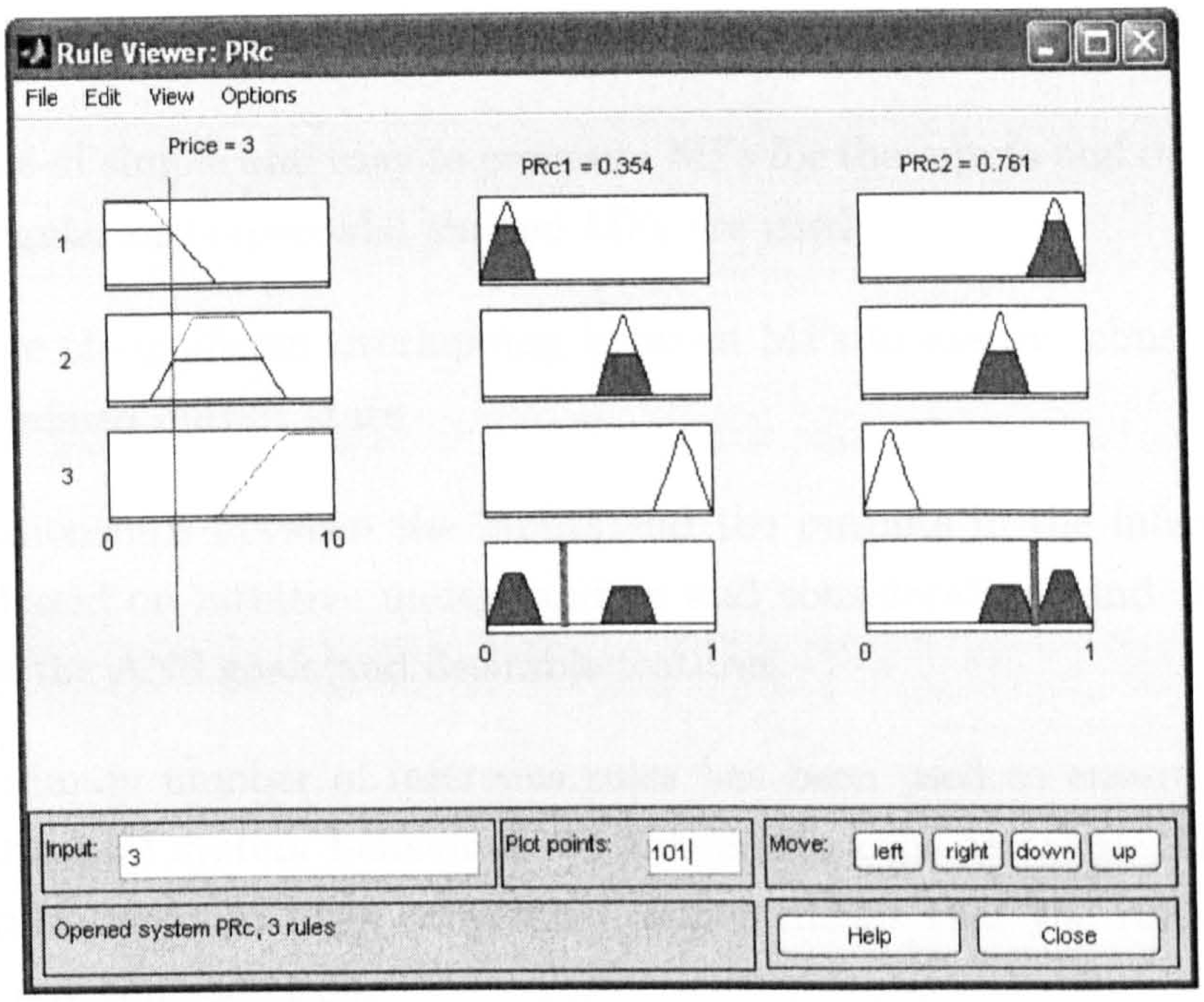

Figure 4.28: "PR_{c1}" and "PR_{c2}" values for user "A"

4.8 Discussion

A novel generic operator terminal-assisted network-controlled ANS algorithm that is based on the developed framework in chapter 3 has been built in this chapter. The developed algorithm works on an HWN that contains co-existed WWAN and WLAN networks. It uses parallel FL and SMART MCDM tool. Four important ANS criteria have been considered. The considered criteria include the received signal strength, the mobile station speed, the service type and the preferred price by user. The developed algorithm can be tailored to specific wireless standards such as UMTS, GSM, HSDPA, GPRS, IEEE802.16x, IEEE802.15x, and IEEE802.11x.

Several considerations have to be taken into account when designing and implementing the FL systems to achieve simple and robust design. The following is a set of considerations that have been taken into account while we were developing our four parallel FL systems.

- The universes of discourses definitions make sure that the universes are not too small, so the input will not be off the scale. They also make sure that the universes are not too wide, so the Membership Functions (MFs) in both left and right will not affect the overall system performance when trying to capture the rare extreme input values.

- The usage of simple and easy to compute MFs for the inputs and outputs. Mainly, the triangular or trapezoidal shaped MFs are used.

- The usage of significant overlapping between MFs to ensure robust inference and usually defined output state.

- The relationships between the inputs and the outputs in the inference rules are mainly based on intuitive understanding and considerations and should consider carefully the ANS goals and desirable features.

- The maximum number of inference rules has been used to ensure that all kinds of situations of system behaviour are taken into consideration. The consistency of the rules has also been considered, which means that the rule base does not contain any contradiction.

- The CoA method has been used for defuzzification because it is the most accurate and widely used method. In addition, it does not suffer from ambiguity and can work in any situation because it usually has a defined state.

The SMART MCDM tool has been chosen and used. The SMART employs a relatively uncomplicated and straightforward manipulation method, which makes it stronger and easier to use in a hybrid and more complex models such as the developed one in this study. It is highly recommended to use such simple methods when more number of RATs or criteria are added.

The developed algorithm in this chapter considers only the co-existence of two types of networks (i.e. WWAN and WLAN). More complicated situation where more RATs are existed need to be investigated in order to test the scalability of the ANS solving framework. In the next chapter, a new operator ANS algorithm that considers the coexistence of three RATs is developed.

To get better understanding and deeper insights into the selection decision making, other advanced MCDM tool has to be used. In the next chapter, the more advanced MCDM tool (AHP) is used.

Although the well stated advantages of the CoA defuzzifaction method, this method is thought to be time consuming and computationally complex. In the next chapter and with the aim of achieving scalable and faster solutions, the pre-defuzzified zero-order

Sugeno FIS (see Appendix A) is used instead of Mamadani FIS that is used in this chapter.

Chapter 5

Combined FL and AHP MCDM for Operator ANS Algorithm

Any ANS solution has to be scalable and it has to be able to handle the increased number of RATs with controlled complexity. This chapter presents a new and novel OSA based on FL and AHP MCDM tool for a co-existing WWAN, WLAN, and WMAN. Although the developed algorithm in chapter 4 and the algorithm developed in the current chapter are both based on the same framework (that is developed in chapter 3) and are both based on the same four criteria addressed in the previous chapter, they have several different aspects. The main differences between both algorithms are summarized in the following points.

- In the previous algorithm, the number of RATs is only two (i.e. WWAN and WLAN). The number of RATs in the current algorithm is three (i.e. WWAN, WLAN, and WMAN). By increasing the number of RATs, the scalability of the developed framework is tested.

- In the previous algorithm, the simple SMART MCDM tool has been used. In the current algorithm, the more advanced AHP MCDM is used. The usage of AHP can bring better understanding and deeper insight into the selection decision making.

- The zero-order Sugeno FIS [130, 127] (see Appendix A) is used instead of the Mamadani FIS. The aim of using Sugeno FIS is to reduce the increased complexity of the inference system due to the increased number of RATs, which allows a more scalable solution.

This chapter consists of three main sections. In the first section, the FL component is described and the differences with the FL component in the previous chapter are highlighted. The second section presents the details of AHP usage in the ANS solution. The third section illustrates the developed solution by means of numerical examples. Figure 5.1 shows the new solution.

5.1 The FL Component

Like the OSA that is developed in chapter 4, the current OSA contains four parallel FL based systems (i.e. RSS, MSS, ST, and PRc systems). The four parallel FL systems are described in this section. The used membership functions for the input variables are the same membership functions used in the previous OSA, so they will not be described again in this chapter. However, due to the increased number of RATs, the number and

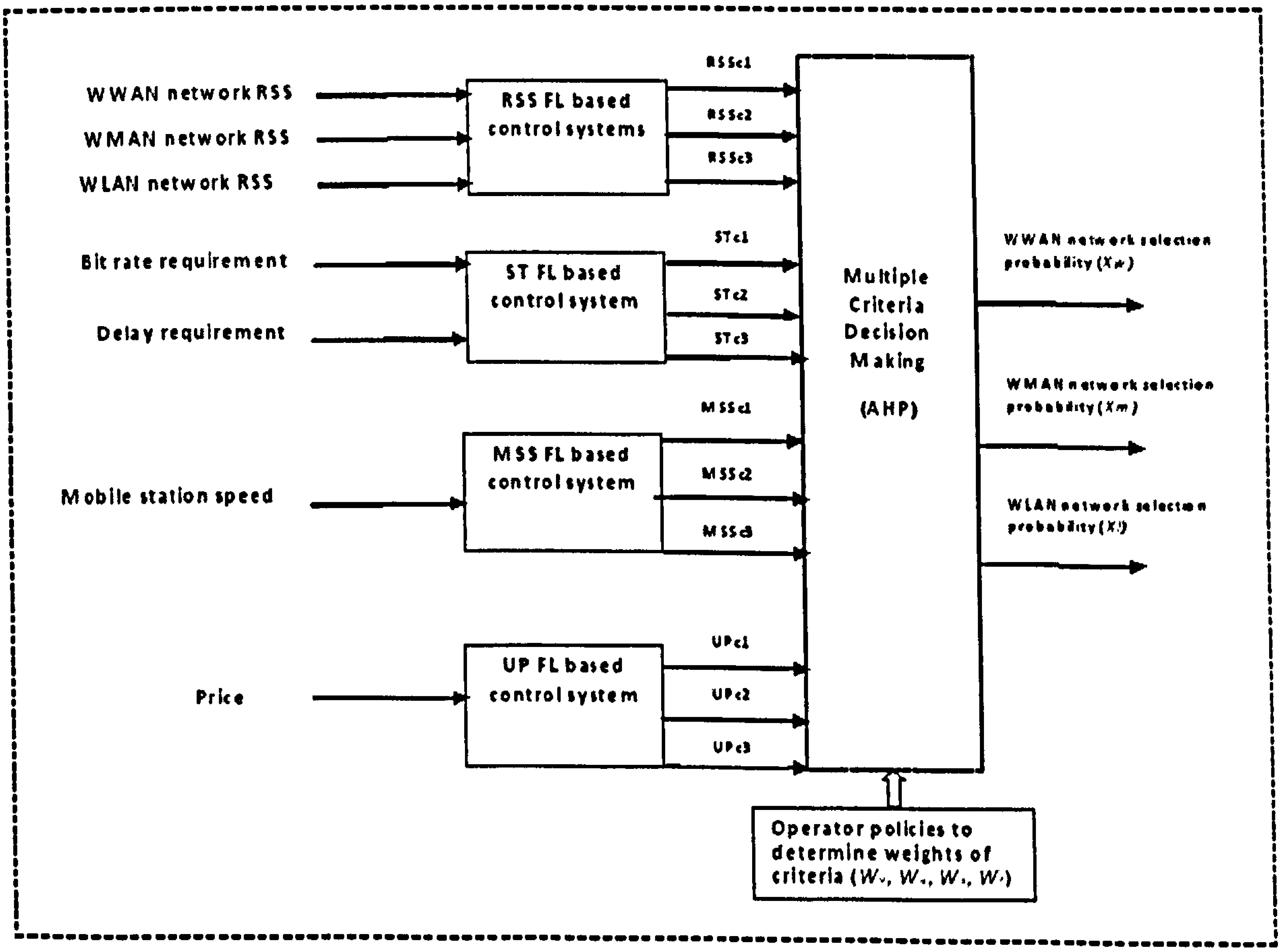

Figure 5.1: ANS OSA for co-existed WWAN, WMAN, and WLAN

type of rules and the control surfaces of the output variables are different. In addition, the used inference system is Sugeno based rather than Mamadani based.

5.1.1 The RSS FL based Systems

To design the RSS system, the received signals' strengths from the three RATs have to be considered. The system has three input variables RSS_1, RSS_2, and RSS_3. It has three output variables RSS_{c1}, RSS_{c2}, and RSS_{c3}. Each input variable describes the received signal strength from one RAT and each output variable describes the initial preference score for one RAT according to the RSS criterion. Figure 5.2 shows the RSS FL system.

The FL system in Figure 5.2 has one clear and considerable problem, which is the big number of inference rules that makes the system more complicated to be built and non-scalable for more RATs. The system could have up to 27 complex inference rules. Table 5.1 shows our first attempt to build the inference rules for this system using the maximum number of fuzzy inference rules.

The table shows the large number of complex inference rules, where the antecedents and consequents of the rules contain three variables. The rules are much more complex

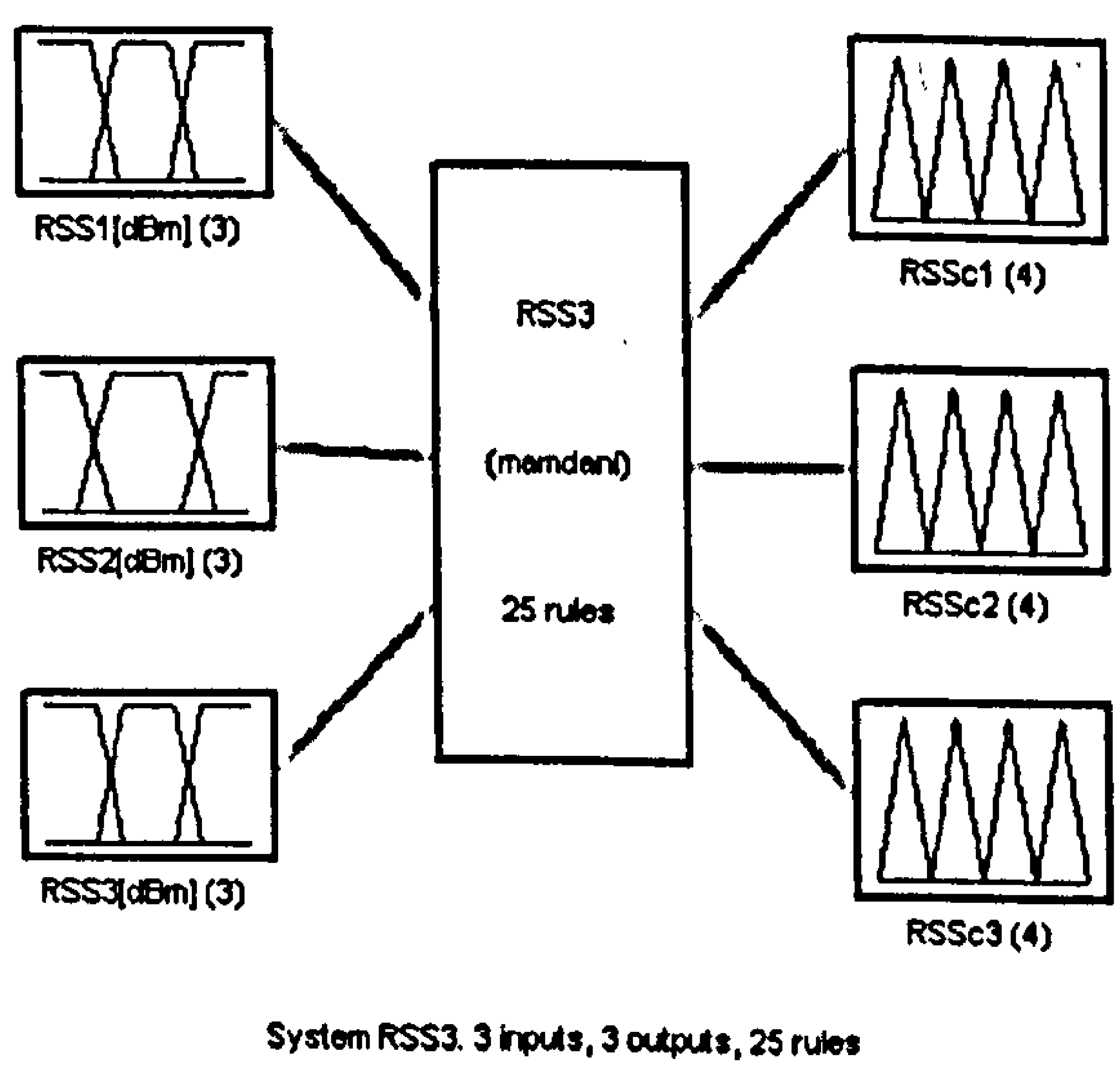

Figure 5.2: The RSS FL system

Table 5.1: The inference rules of the multi-input multi output RSS FL based system

Rule No.	RSS_1	RSS_2	RSS_3	RSS_{c1}	RSS_{c2}	RSS_{c3}
1	H	H	H	TA	TA	TA
2	H	H	M	TA	TA	PA
3	H	M	L	TA	PA	PR
4	M	M	H	PA	TA	TA
5	M	L	M	PA	TR	PA
6	H	M	M	TA	PA	PA
7	L	L	H	TR	TR	TA
8	L	H	M	PR	PA	PA
9	L	M	L	TR	PA	TR
10	H	M	H	TA	PA	TA
11	H	L	M	TA	TR	PA
12	H	L	L	TA	TR	TR
13	M	H	H	PA	TA	TA
14	M	H	M	PA	TA	PA
15	M	M	L	PA	PA	TR
16	L	M	H	PR	TA	TA
17	L	L	M	TR	TR	PA
18	L	L	L	TR	TR	TR
19	H	L	H	TA	TR	TA
20	L	H	L	TR	TA	TR
21	H	H	L	TA	PR	PR
22	M	M	H	PA	TA	TA
23	M	L	M	PA	PA	PA
24	M	L	L	PA	TR	TR
25	L	H	H	TR	TA	TA
26	L	M	M	TR	PA	PA
27	M	M	M	PA	PA	PA

with more RATs. To reduce the complexity involved with the developed RSS FL system when the number of RATs is increased, the system is divided into three Single-Input Single-Output (SISO) systems. Each system has only one input variable and only one output variable. Each system is dedicated for one RAT.

Figure 5.3 shows the SISO RSS system for the WWAN network (named as RSSc31) as an example. The other two SISO RSS systems for the WLAN and WMAN networks (named as RSSc32 and RSSc33) have similar structures.

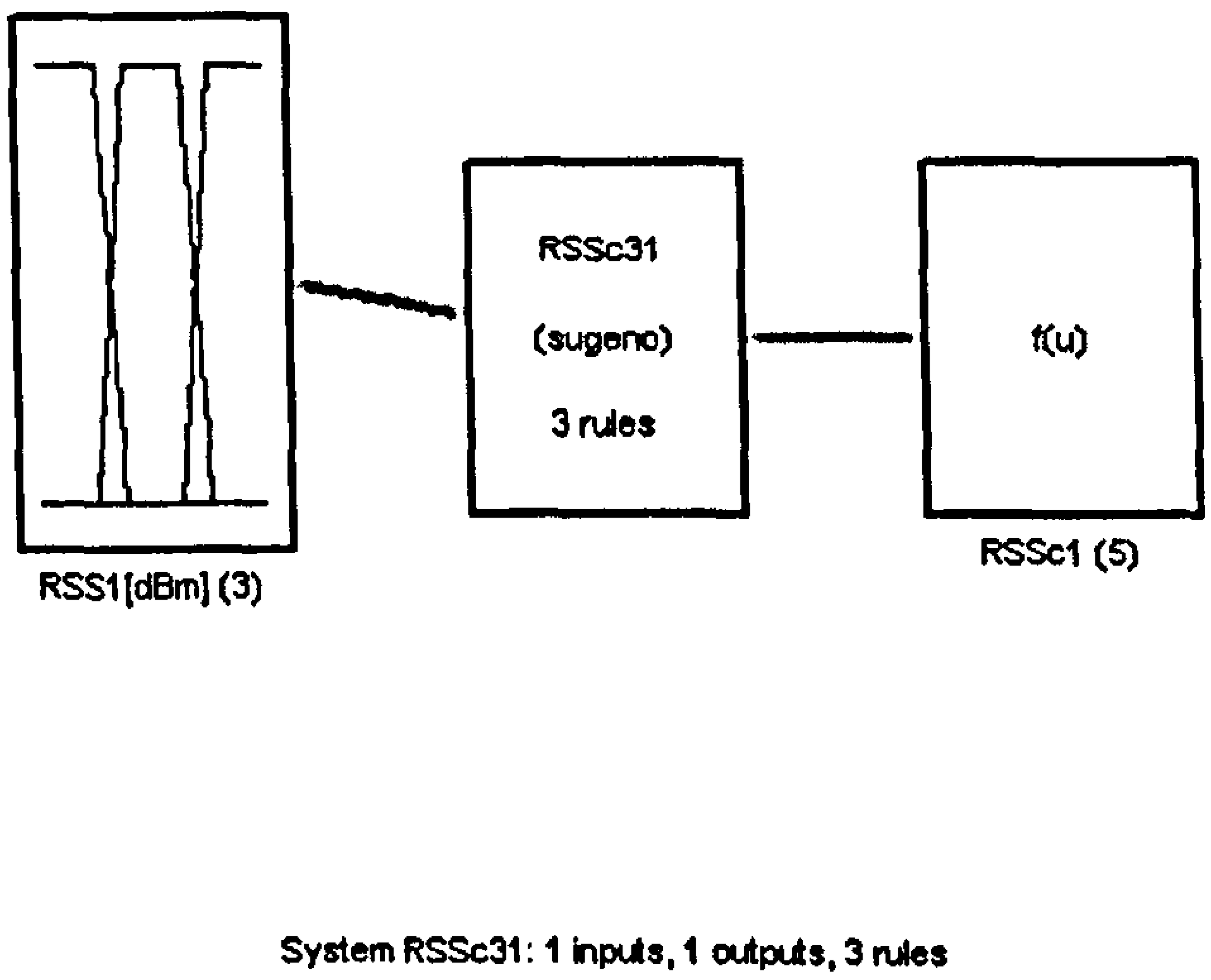

Figure 5.3: The RSSc31 single input single output FL system

RSSc31 FL system has only three very simple rules, where the antecedent and consequent of each rule contains only one variable. The rules have been built with the aim of assigning the users to the network with the stronger signal. Therefore, when the value of the input variable is increased, the value of the output variable is increased too. Table 5.2 shows the rules of the RSSc31 FL system as an example. For example, the second inference rule can be read as "If the received signal from WWAN network is medium, the WWAN has equal probability to be selected or to be rejected".

Table 5.2: The inference rules of the RSSc31 FL based system

Rule No.	RSS_1	RSS_{c1}
1	L	TR
2	M	EP
3	H	TA

Figure 5.4 shows the control surface for the output variables RSS_{c1} as an example. The figure shows the expected behaviour from the RSS_{c1} system, where the value of RSS_{c1} is becoming higher when the received signal from the WWAN is going stronger. Appropriate behaviours are also achieved by RSS_{c2} and RSS_{c3}.

Each output variable (i.e. RSS_{c1}, RSS_{c2} or RSS_{c3}) has five constant membership functions {Totally Reject (TR), Probability Reject (PR), Equal Probability (EP), Probability Accept (PA), Totally Accept (TA)}. TR indicates that the current RAT has to be totally rejected according to the RSS criterion. PR indicates that the current RAT has to be rejected with high probability according to the same criterion. EP indicates that the current RAT has an equal chance to be selected or rejected for the user. PA indicates that the current RAT has to be accepted with high probability. TR indicates that the current RAT has to be totally accepted according to the RSS criterion. All the output membership functions are represented using single spike (i.e. singleton) rather than a distributed fuzzy set. It can be thought of as a pre-defuzzified fuzzy set and it greatly simplifies the computation required by the more general Mamdani method, which allows for more scalable solutions.

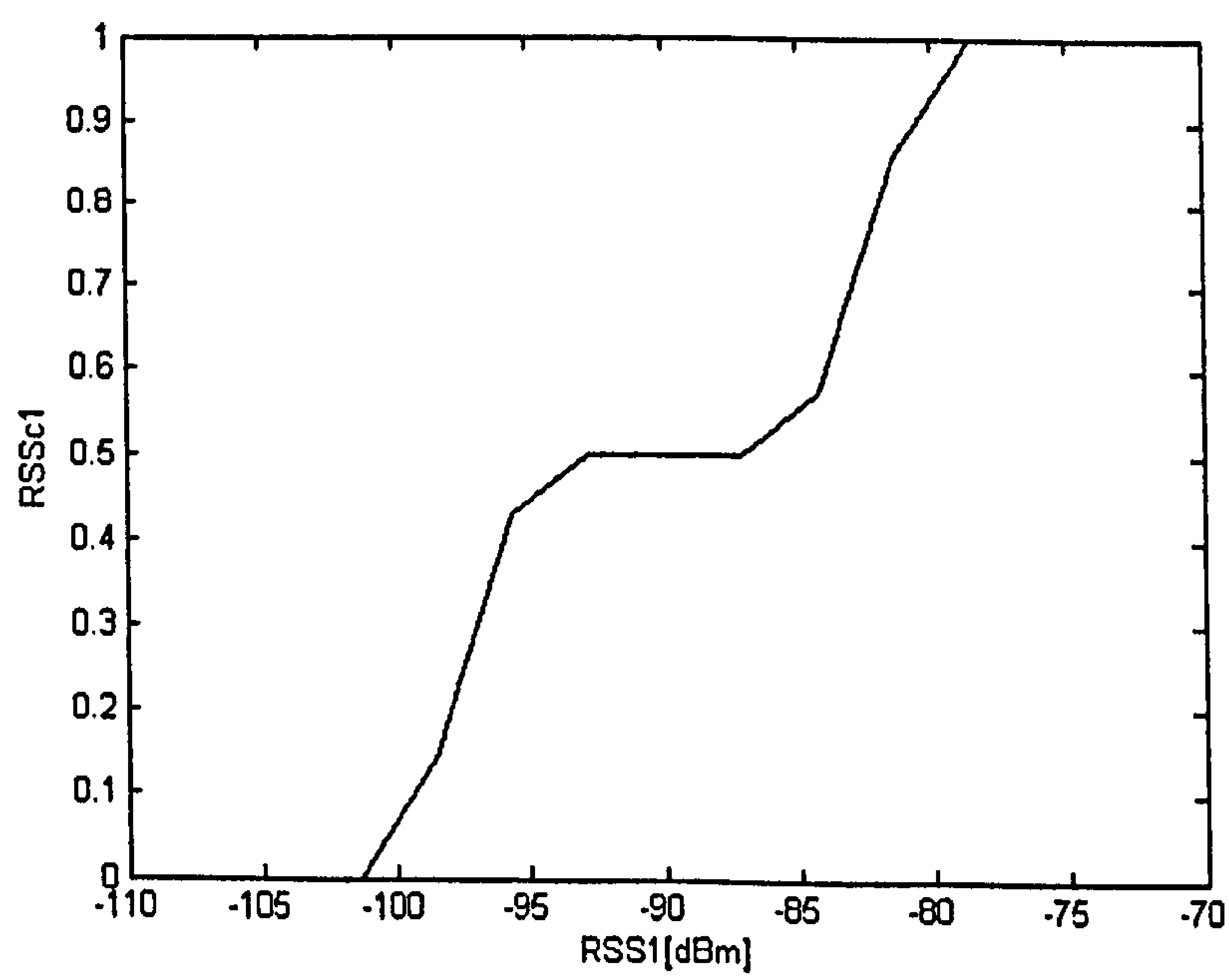

Figure 5.4: The control surface of the variable RSS_{c1}

5.1.2 The MSS FL based System

Figure 5.5 shows the MSS FL system. The system has one input variable MSS to describe the mobile station speed. MSS has the same universe of discourse and membership functions mentioned in the previous chapter. The system also has three output variables, namely MSS_{c1}, MSS_{c2}, and MSS_{c3}. Each output variable describes one RAT score against the MSS criterion.

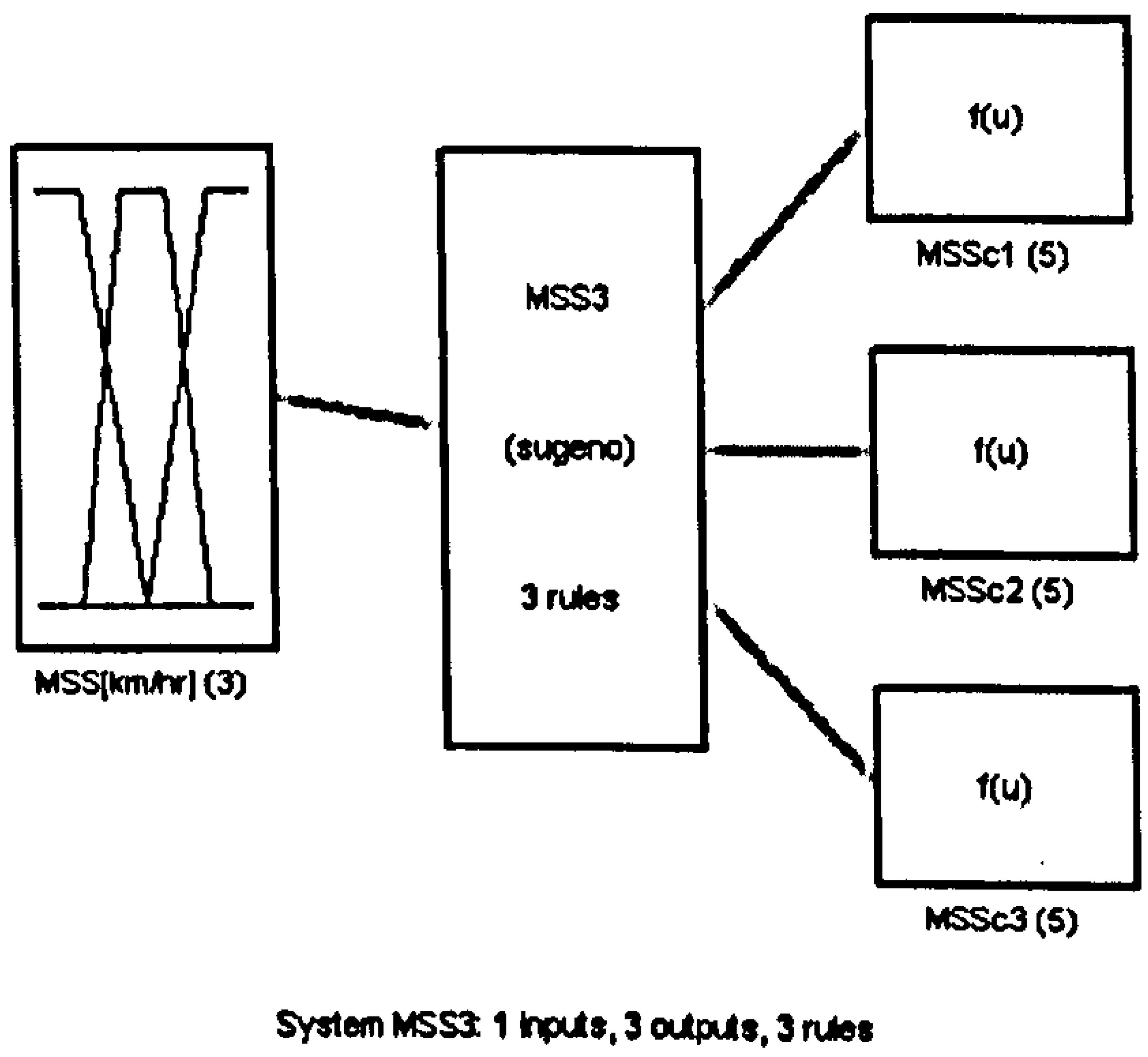

Figure 5.5: The MSS FL system

The MSS system has only three inference rules. They have been designed with the aim to assign the user with high speed to the RAT with a larger coverage area and to assign the user with low speed to the smaller coverage area RAT. For example, the second inference rule can be read as "If the mobile station speed is medium, the probability accept the WWAN, probability reject the WLAN and totally accept the WMAN".

Table 5.3: The inference rules of the MSS FL based system

Rule No.	MSS	MSS_{c1}	MSS_{c2}	MSS_{c3}
1	L	TR	TA	PR
2	M	PA	PR	TA
3	H	TA	TR	PR

Figure 5.6 shows the control surface for the output variable MSS_{c1}. The figure shows that the chance of selecting the WWAN network increases (i.e. MSS_{c1} increases), when the value of MSS increases because WWAN is a large-area coverage network. Appropriate behaviours are also achieved by MSS_{c2} and MSS_{c3}. MSS_{c2} decreases when the value of MSS increases because the WLAN is a small-area coverage network. MSS_{c3} increases when the value of MSS increases until a specific point where MSS becomes very high, then the MSS_{c3} starts decreasing.

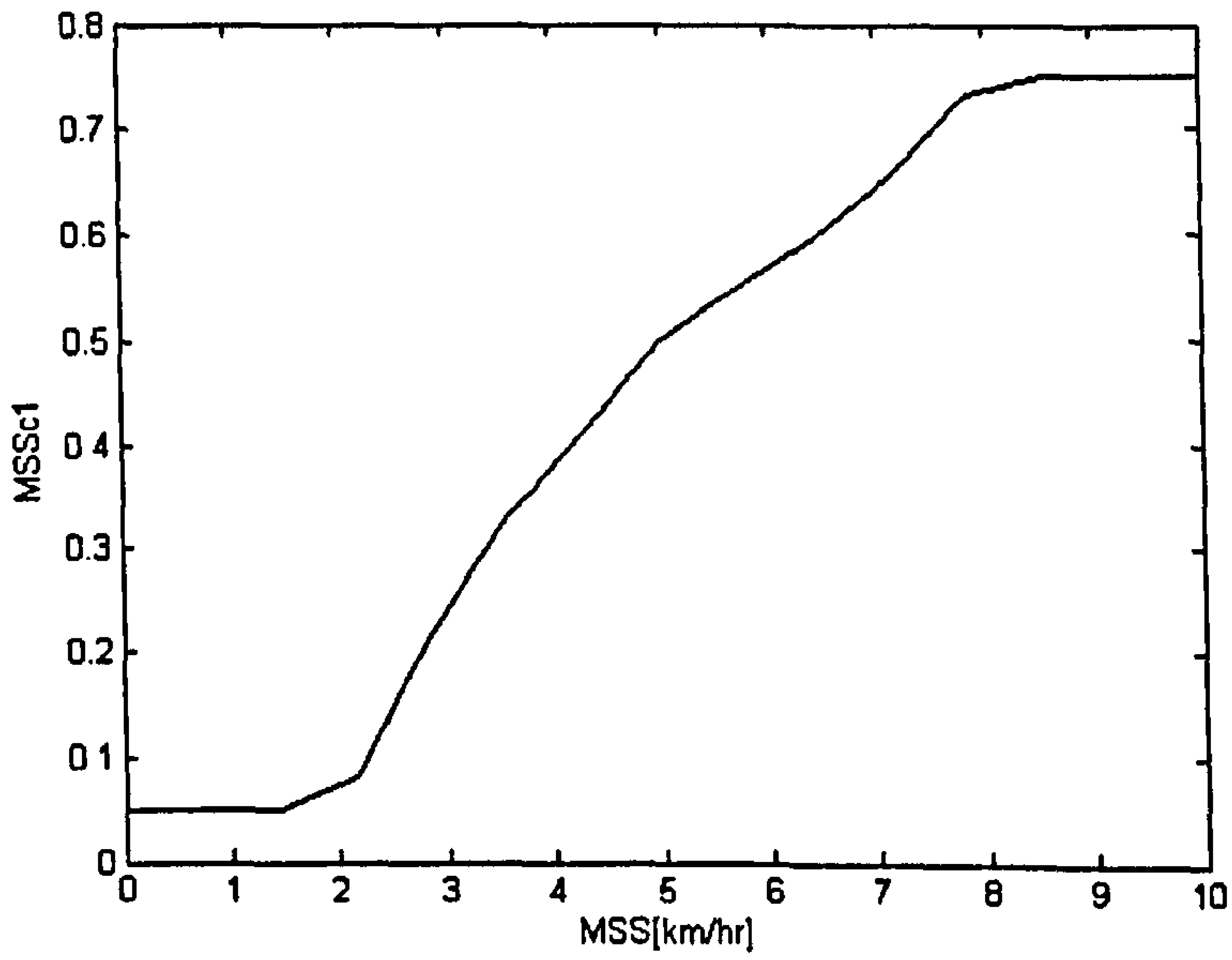

Figure 5.6: The control surface of the variable MSS_{c1}

Each output variable has five constant membership functions {Totally Reject (TR), Probability Reject (PR), Equal Probability (EP), Probability Accept (PA), Totally Accept (TA)}. TR indicates that the current RAT has to be totally rejected according to the MSS criterion. PR indicates that the current RAT has to be rejected with high probability according to the MSS criterion. EP indicates that the current RAT has an equal chance to be selected or rejected for the user according the MSS criterion. PA indicates that the current RAT has to be accepted with high probability according to the MSS criterion. TR indicates that the current RAT has to be totally accepted according to the MSS criterion. Again, singleton membership functions are used for the output variables.

5.1.3 The ST FL based System

Figure 5.7 shows the ST FL system. The system has two input variables, *DelayReqc* and *RateReqc*, to describe the one-way propagation delay and bit rate requirements respectively. Both variables have the same universe of discourse and membership functions mentioned in the previous algorithm that has been developed in chapter 4. Also, the system has three output variables, namely ST_{c1}, ST_{c2}, and ST_{c3}. Each variable describes the network score against the ST criterion.

The ST FL based system has nine rules as shown in table 5.4. The inference rules of the ST system are designed to assign the service requests with strict delay propagation time and low bite rate requirements to the WWAN networks, to assign the service requests with low propagation delay and high bit rate requirements to the WLAN network, and to assign the services with medium propagation delay and bit rate requirements to the WMAN network. For example, the fifth inference rule can be read as "If the delay and bit rate requirements are medium, then probability accepts the WWAN, WLAN and MAN".

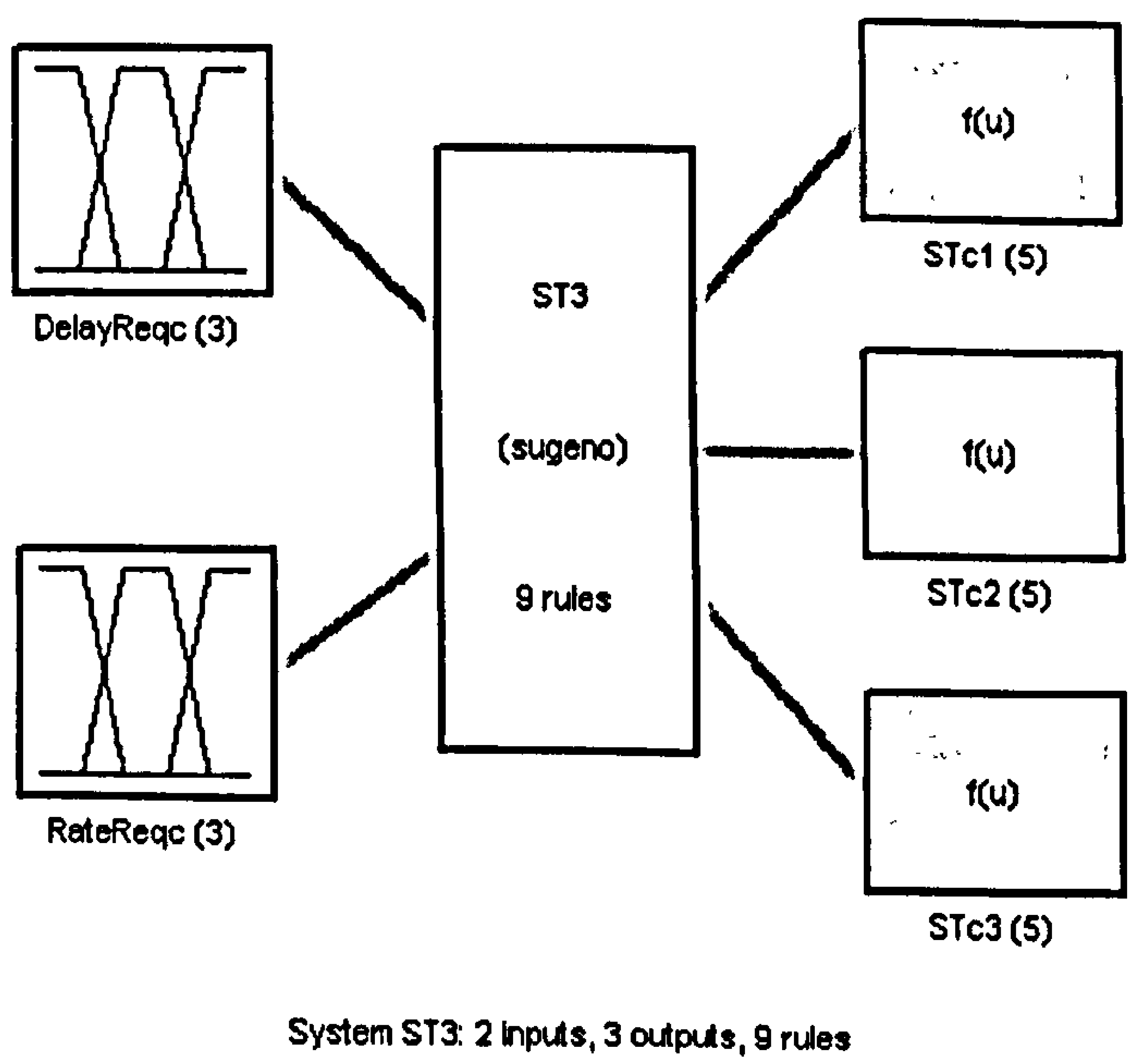

Figure 5.7: The ST FL system

Table 5.4: The inference rules of the ST FL based system

Rule No.	*DelayReqc*	*RateReqc*	ST_{c1}	ST_{c2}	ST_{c3}
1	H	L	TA	TR	PR
2	H	M	PA	PR	PA
3	H	H	PA	PA	PA
4	M	L	PA	PR	PA
5	M	M	PA	PA	PA
6	M	H	PR	PA	PA
7	L	L	PA	PA	PA
8	L	M	TR	TA	TA
9	L	H	TR	TA	PA

Figure 5.8 shows that by decreasing the value of "*DelayReqc*" or the value of "*RateReqc*", the chance of selecting the WWAN network increases (i.e. ST_{c1} increases). If both variables decrease together, the chance of selecting the WWAN network becomes higher. Appropriate behaviours are also achieved by ST_{c2} and ST_{c3}.

One important advantage to notice in the current surfaces over the same variables' surfaces in the previous algorithm (that has been developed in chapter 4) is the usage of the full range of the output variable (from 0 to 1). This advantage is due to the usage of the Sugeno type, which can bring the output variables to extremist values.

The membership functions of the output variables have the same structure and values used in the RSS31 and MSS systems. Five membership function are used {TR, PR, EP, PA, TA} to reflect the degree of RAT attractiveness according to the ST criterion.

5.1.4 The PRc FL based System

Figure 5.9 shows the PRc FL system. PRc system has only one input variable "*Price*" to describe the user preferred price. The system has three output variables PR_{c1}, PR_{c2}, and PR_{c3}.

Table 5.5 shows the three simple inference rules of the PRc FL based system. The PRc FL inference rules are designed so the users with a low-price target are assigned to the WLAN because of its low cost. The users with high price target are assigned to WWAN, which usually costs more. The users with a medium price target are assigned

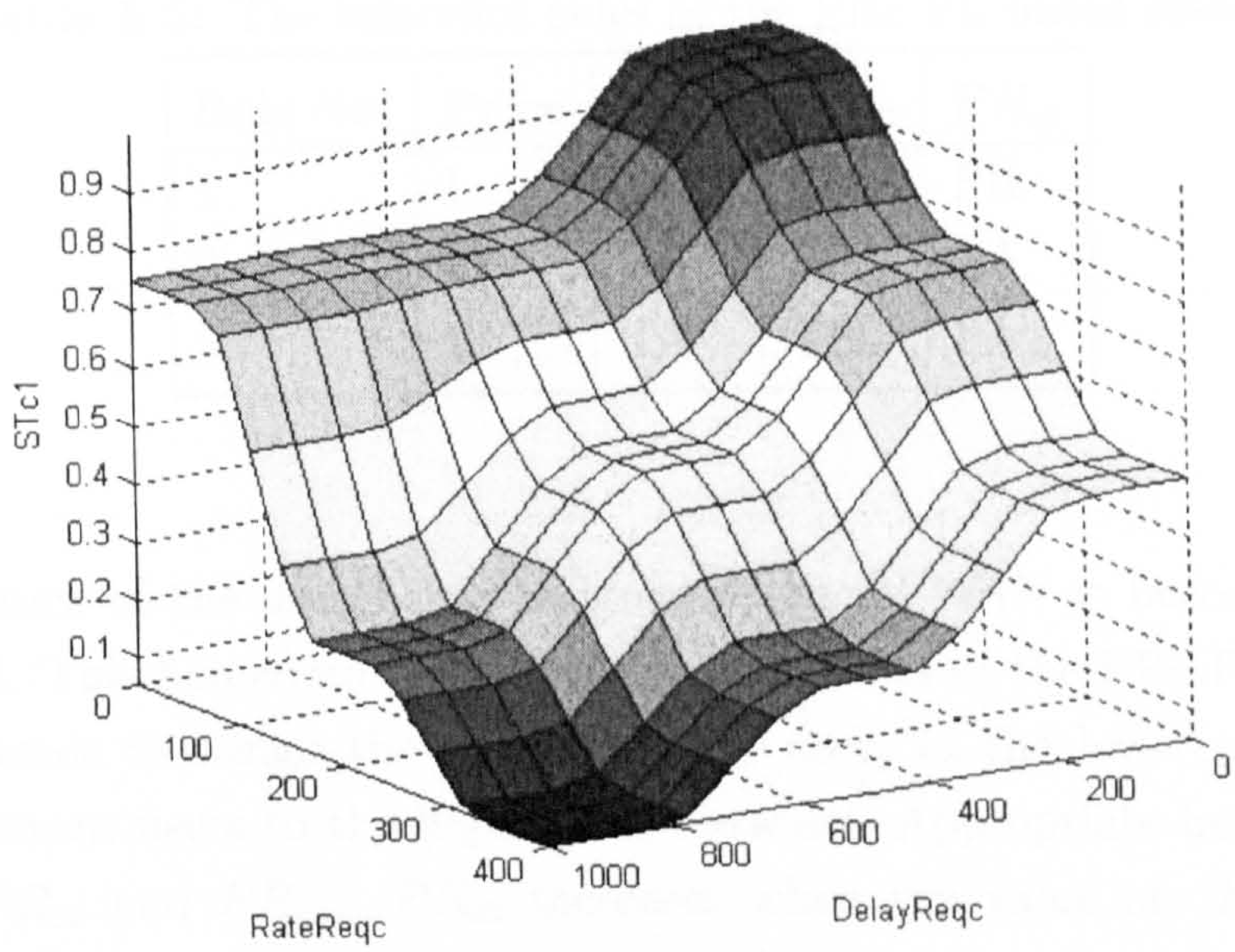

Figure 5.8: The control surface of the ST_{c1}

to WMAN.

Figure 5.10 shows that when the user can pay more (i.e. higher "*Price*" variable

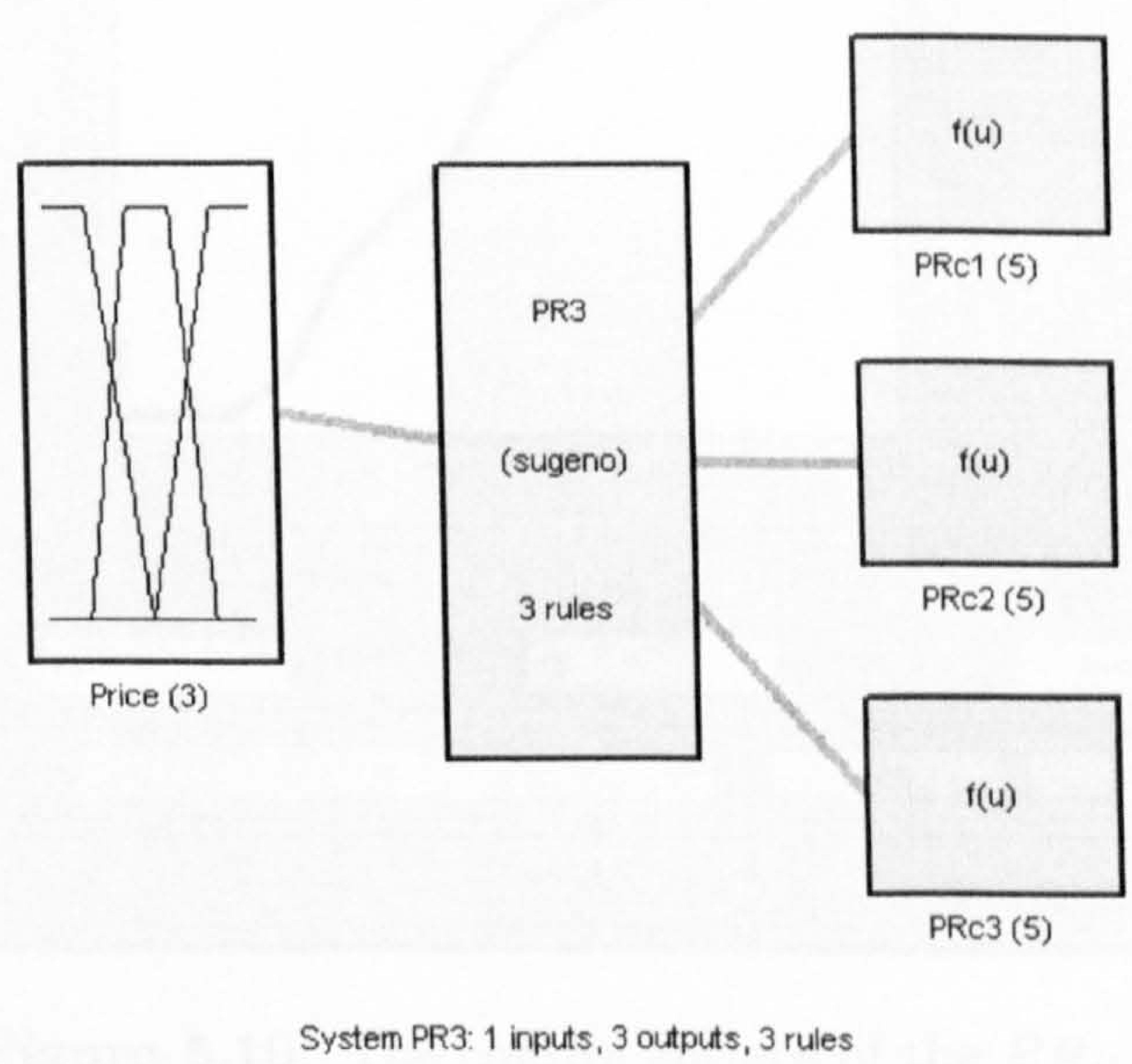

Figure 5.9: The PRc system

Table 5.5: The inference rules of the PRc FL based system

Rule No.	*Price*	PR_{c1}	PR_{c2}	PR_{c3}
1	L	TR	TA	PR
2	M	PA	PR	TA
3	H	TA	TR	PA

value), the chance of the user being assigned to the WWAN is becoming higher (i.e. PR_{c1} increase). This behaviour reflects the requirements of the PRc FL system, where the operator needs to assign the less important users to the lower cost network and the more important users to the higher cost network. Appropriate behaviours are also achieved by PR_{c2} and PR_{c3}. PR_{c2} increases when the value of "*Price*" decreases, because the WLAN is a low cost network. PR_{c3} increases when the value of *Price* increases until a specific point where *Price* becomes very high, then the PR_{c3} starts decreasing.

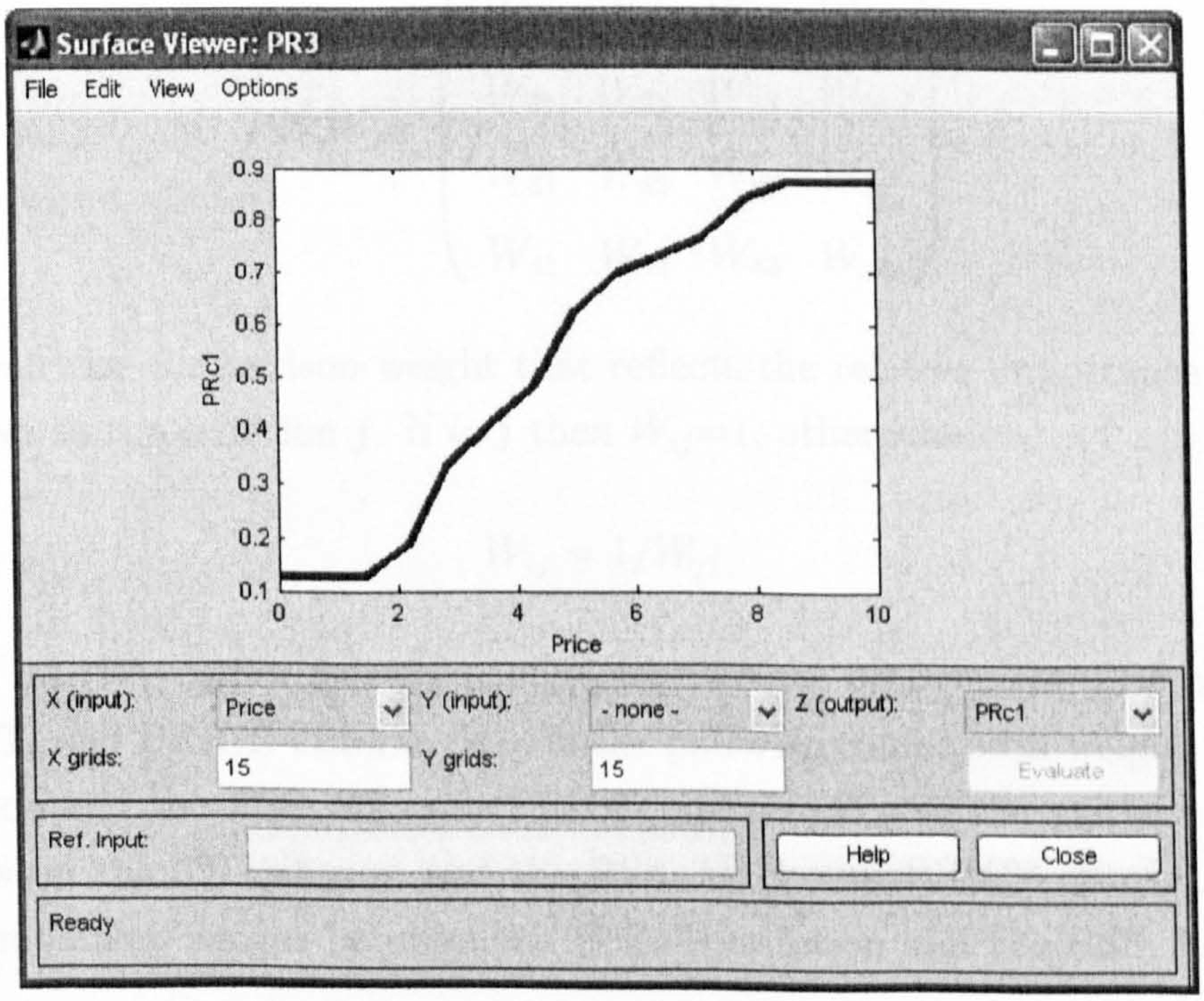

Figure 5.10: The control surface of the PR_{c1}

5.2 The MCDM Component

The MCDM system has to rank the considered alternatives according to their attractiveness. The MCDM system aims to a) achieve the highest number for satisfied users, b) achieve the highest number of the users who get better quality, and c) save the resources of high cost networks by increasing the usage of low cost networks. The MCDM has three alternatives to consider, the first one is a WWAN network, the second one is a WLAN network and the third one is a WMAN network. The input criteria of the MCDM are the RSS, MSS, ST, and PRICE. The AHP decision making tool that is described in subsection 2.5.2 is used. AHP allows the complex problems with many criteria and alternatives to be solved through decomposition. It allows the different aspects of the problem to be examined in detail and its true and relative importance to be established. AHP has a hierarchical structure, which provides a simple visualization for the problem. The steps of applying AHP to the ANS problem are described as follows:

Step1: The pairwise comparison of criteria: the criteria pairwise weight comparison matrix PWW is described as in equation 5.1.

$$PWW = \begin{pmatrix} W_{11} & W_{12} & W_{13} & W_{14} \\ W_{21} & W_{22} & W_{23} & W_{24} \\ W_{31} & W_{32} & W_{33} & W_{34} \\ W_{41} & W_{42} & W_{43} & W_{44} \end{pmatrix} \tag{5.1}$$

W_{ij} is the pairwise comparison weight that reflects the relative importance of criterion i with respect to the criterion j. If i=j then W_{ij}=1, otherwise

$$W_{ij} = 1/W_{ji} \tag{5.2}$$

In equation 5.1, W_{1j} is the pairwise comparison weight between the RSS criterion and the MSS, ST, and PRICE criteria. W_{2j} is the pairwise comparison weight between the MSS criterion and the RSS, ST, and PRICE criteria. W_{3j} is the pairwise comparison weight between the ST criterion and the RSS, MSS, and PRICE criteria. W_{4j} is the pairwise comparison weight between the PRICE criterion and the RSS, MSS, and ST criteria.

W_{ij} could be any number between 1 and 9. W_{ij} = 1 indicates equal importance or preference. W_{ij} = 3 indicates moderate importance or preference of one over another. W_{ij} = 5 indicates strong or essential importance or preference. W_{ij} = 7 indicates very strong or demonstrated importance or preference. $W_{ij} = 9$ indicates extreme importance or preference.

Step2: calculating the criteria priority vector or the normalized criteria weights: to calculate the Normalized Criteria Weights (NCW), the Geometric Mean (GM) is used. GM is less affected by extreme values than the arithmetic mean. In general, the geometric mean is the nth root of the product of the n pairwise comparison weights of the criteria. In our case, it is the 4th root of the product of the 4 pairwise comparison weights of the criteria. In general, the geometric mean of the i criterion weight GM_i is calculated as in equation 5.3

$$GM_i = \sqrt[4]{\Pi_{j=1}^{4} W_j} \tag{5.3}$$

For example, the geometric mean of the RSS criterion weight GM_{RSS} is calculated as shown in equation 5.4.

$$GM_{RSS} = \sqrt[4]{W_{11} \cdot W_{12} \cdot W_{13} \cdot W_{14}} \tag{5.4}$$

After calculating the geometric mean, the normalized weights of the different criteria NCW are calculated. In general, the normalized weight of the i criterion NCW_i is calculated by dividing its geometric mean GM_i by the sum of the geometric means of all the criteria as shown in equation 5.5.

$$NCW_i = \frac{GM_i}{\sum_{j=1}^{4} GM_{ij}} \tag{5.5}$$

The normalized weights for the RSS, MSS, ST, and PRICE criteria are calculated as shown in equations 5.6, 5.7, 5.8, and 5.9 respectively.

$$NCW_{RSS} = \frac{GM_{RSS}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} \tag{5.6}$$

$$NCW_{MSS} = \frac{GM_{MSS}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} \tag{5.7}$$

$$NCW_{ST} = \frac{GM_{ST}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} \tag{5.8}$$

$$NCW_{PRICE} = \frac{GM_{PR}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} \tag{5.9}$$

The matrix of the normalized weights $NCWM$ is shown in equation 5.10.

$$NCWM = \begin{pmatrix} NCW_{RSS} \\ NCW_{MSS} \\ NCW_{ST} \\ NCW_{PRICE} \end{pmatrix} \tag{5.10}$$

Step 3: pairwise comparison of alternatives with respect to criteria: three alternatives WWAN, WMAN, and WLAN are considered. Arrays of dimensions 3X3 are used to represent the pairwise comparison matrices of alternatives' scores with respect to the different criteria. Equation 5.11 shows a general pairwise comparison matrix of alternatives' scores with respect to one criterion PWS.

$$PWS = \begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \tag{5.11}$$

S_{ij} is the pairwise comparison of the i and j alternatives' scores with respect to one criterion. For the RSS criterion, it is calculated according to equation 5.12.

$$_{r}S_{ij} = RSSc_i / RSSc_j \tag{5.12}$$

The pairwise comparison of alternatives' scores with respect to MSS criterion $_{m}S_{ij}$ is calculated according to equation 5.13

$$_{m}S_{ij} = MSSc_i / MSSc_j \tag{5.13}$$

The pairwise comparison of alternatives' scores with respect to ST criterion $_{s}S_{ij}$ is calculated according to equation 5.14

$$_{s}S_{ij} = STc_i / STc_j \tag{5.14}$$

The pairwise comparison of alternatives' scores with respect to PRICE criterion $_{p}S_{ij}$ is calculated according to equation 5.15

$$_{p}S_{ij} = PRc_i / PRc_j. \tag{5.15}$$

Step4: calculating the normalized alternative score with respect to criteria: to calculate the normalized alternative score, again, the geometric mean is used. The geometric mean for the normalized alternative score is the 3rd root of the product of the 3 pairwise scores of the alternative. In general, the geometric mean of the i alternative's score with respect to one criterion j is calculated as shown in equation 5.16

$$GM_i = \sqrt[3]{\Pi_{j=1}^{3} S_{ij}} \tag{5.16}$$

For example, the geometric mean of the WWAN score with respect to criterion j, $_{j}GM_{WWAN}$, is calculated as shown in equation 5.17

$$_{j}GM_{WWAN} = \sqrt[3]{S_{11} \cdot S_{12} \cdot S_{13}} \tag{5.17}$$

Then, the normalized score of the i alternative NS_i with respect to one criterion j is calculated by dividing its geometric mean by the sum of the geometric means of all the alternatives as in equation 5.18

$$_{j}NS_i = \frac{GM_i}{\Pi_{j=1}^{3} GM_j} \tag{5.18}$$

For example, the normalized weights for the WWAN, WMAN, and WLAN alternatives with respect to the RSS criterion are calculated as shown in equations 5.19, 5.20, and 5.21 respectively.

$$_{r}NS_{WWAN} = \frac{_{r}GM_{WWAN}}{_{r}GM_{WWAN} +_{r} GM_{WMAN} +_{r} GM_{WLAN}} \tag{5.19}$$

$$_{r}NS_{WLAN} = \frac{_{r}GM_{WLAN}}{_{r}GM_{WWAN} +_{r} GM_{WMAN} +_{r} GM_{WLAN}} \tag{5.20}$$

$$_{r}NS_{WMAN} = \frac{_{r}GM_{WMAN}}{_{r}GM_{WWAN} +_{r} GM_{WMAN} +_{r} GM_{WLAN}} \tag{5.21}$$

The matrix of the normalized alternatives' scores with respect the RSS criterion ${}_rNSM$ is shown in 5.22

$$ {}_rNSM = \begin{pmatrix} {}_rNS_{WWAN} \\ {}_rNS_{WMAN} \\ {}_rNS_{WLAN} \end{pmatrix} \tag{5.22} $$

Step5: calculating the alternatives total scores and identifying the preferred alternative: to identify the preferred alternative, every normalized alternative score with respect to criterion i is multiplied by the corresponding normalized weight of criterion i (i.e. NCW_i) and the results for each alternative with respect to the different criteria are summed. The preferred alternative is the one that has the highest total score ATS. The total score for alternative j ATS_j is calculated according to equation 5.23.

$$ ATS_j = \sum_{i=1}^{4} NCW_i \cdot NS_{ij} \tag{5.23} $$

NCW_i is the normalized weight of the criteria i. NS_{ij} is the normalized score of alternative j with respect to criteria i.

5.3 Illustrative Numerical Examples

This section illustrates the developed algorithm by giving some numerical examples for real cases. Let's assume three users {user "A", user "B", and user "C"}. User "A" has a mobile terminal that has three radio interfaces for UMTS, IEEE 802.11g WLAN, and IEEE 802.16 WMAN networks. While "A" is walking at a speed of 5 km/hr, he is trying to access the Internet to check his email. User "A" prefers to get the services at as low a price as possible. The measured received signals from UMTS, WLAN, and WMAN are -91, -70 and -91 dB respectively. User "B" has a laptop that has the suitable radio interfaces for DVB-H, IEEE802.11g WLAN, and IEEE 802.16 WiMAX. While "B" is sitting in his house, he is trying to watch some online TV channels through the Internet. The measured received signals from DVB-H, WLAN, and WiMAX are -80, -85 and -100 dB respectively. User "C" is running at speed of 7 km/hr, while he is trying to make a voice call using his mobile terminal that could support cdmaOne (i.e. IS-95a), GSM and IEEE 802.11g networks. User "C" is on a micro GSM cell and a macro cdmeOne cell. The measured received signals from cdmaOne, IEEE802.11g, and GSM networks at the mobile terminal interface are -83, -82, and -100 dB respectively. Both users "B" and "C" are waiting for the best quality at any price.

The first step is the pre-processing stage (i.e. ANS initiation phase) where the suitable information required for the selection decision is gathered from the different sources to be available at the CRRM entity, where the developed OSA resides. The RSS_1, RSS_2, and RSS_3 values are measured at the mobile station interfaces and are sent to the CRRM entity. Practically, the averages of these variables that are taken during a specific period of time are used instead of the instance values. The MSS value is measured at the CRRM entity or mobile station using some mobile speed estimation methods. The delay and rate requirements' values depend on the type of the required service as mentioned on section 4.7. The same values used on 4.7 for the delay and rate requirements are used in this section. Users "A", "B" and "C" values for $Price$ variables are assumed to be 3, 7 and 8 respectively. Table 5.6 summarizes the collected information and measurement in the pre-processing step.

Table 5.6: The collected Information from the pre-processing stage

Variable	User "A"	User "B"	User "C"
RSS_1	-91 dB	-80 dB	-83 dB
RSS_2	-78 dB	-85 dB	-82 dB
RSS_3	-91dB	-100 dB	-100dB
MSS	5km/hr	0km/hr	7km/hr
$Price$	3	7	8
$DelayReqc$	800ms	400ms	200ms
$RateReqc$	64kbps	400kbps	12.2kbps

The second step is applying the collected information into the FL parallel systems inputs to get the initial score for each alternative with respect to each criterion. Figures 5.11, 5.12, and 5.13 show the values of RSS_{c1}, RSS_{c2} and RSS_{c3} for user "A". The figures show that the value of both RSS_{c1}, RSS_{c2} and RSS_{c3} are 0.5, 0.5 and 0.5 respectively. By applying the values of the RSS_1, RSS_2 and RSS_3 for user "B" and user "C", we have got 1, 0.5, and 0.05 for user "B" and 0.7, 0.5 and 0.05 for user "C" RSS_{c1}, RSS_{c2} and RSS_{c3} values.

Figure 5.14 shows the values of MSS_{c1}, MSS_{c2} and MSS_{c3} for user "A". The figure

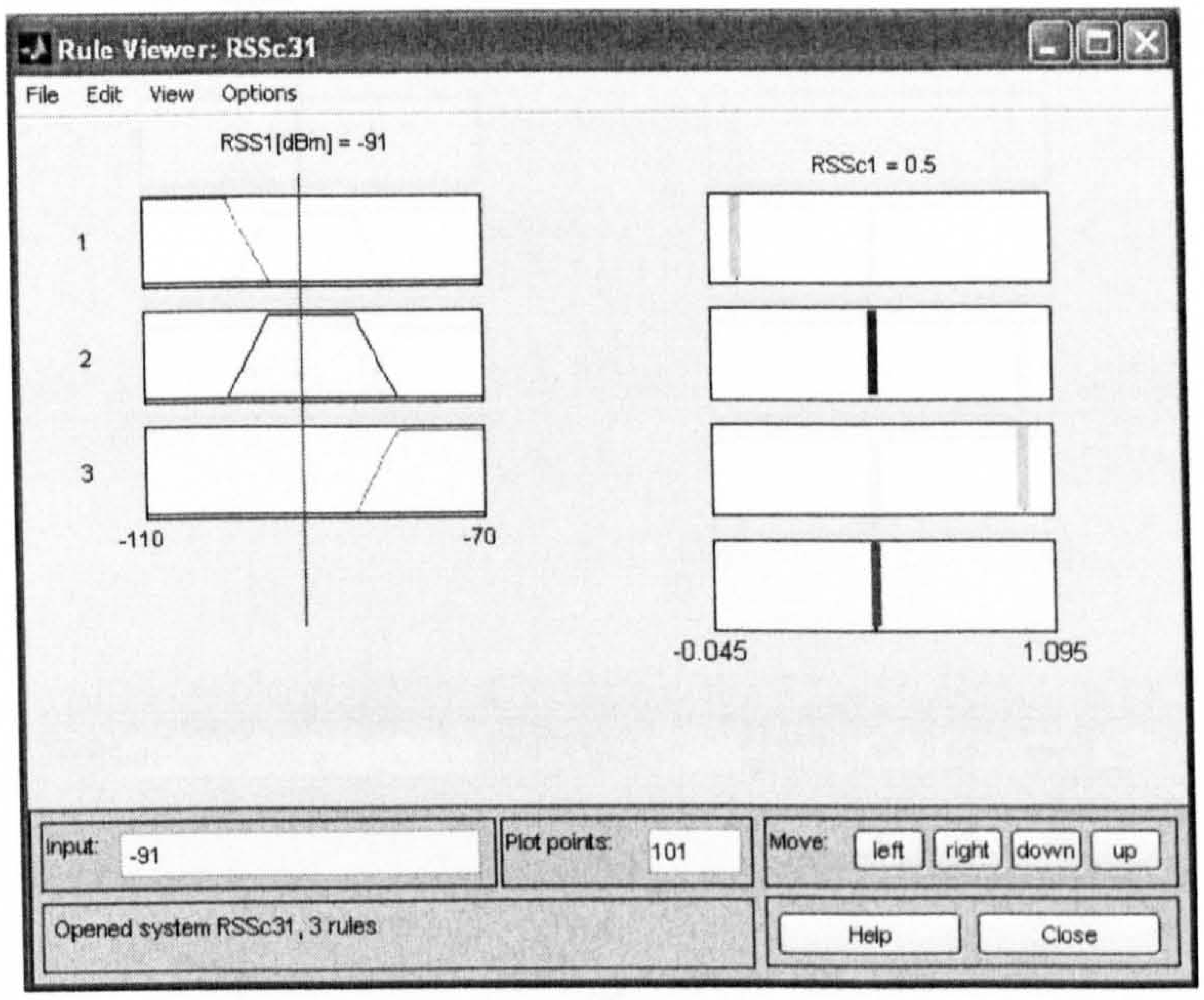

Figure 5.11: RSS_{c1} values for user "A"

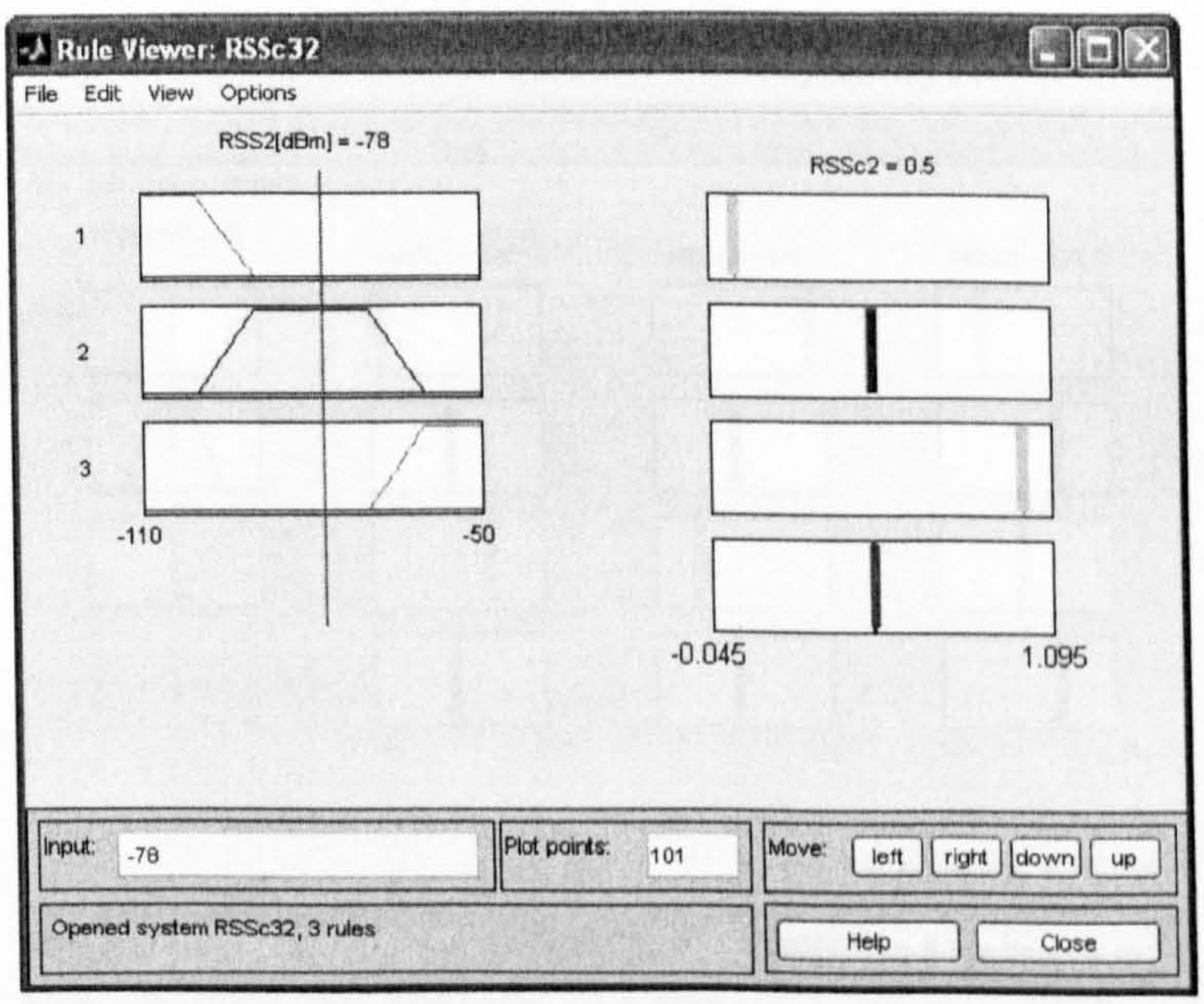

Figure 5.12: RSS_{c2} values for user "A"

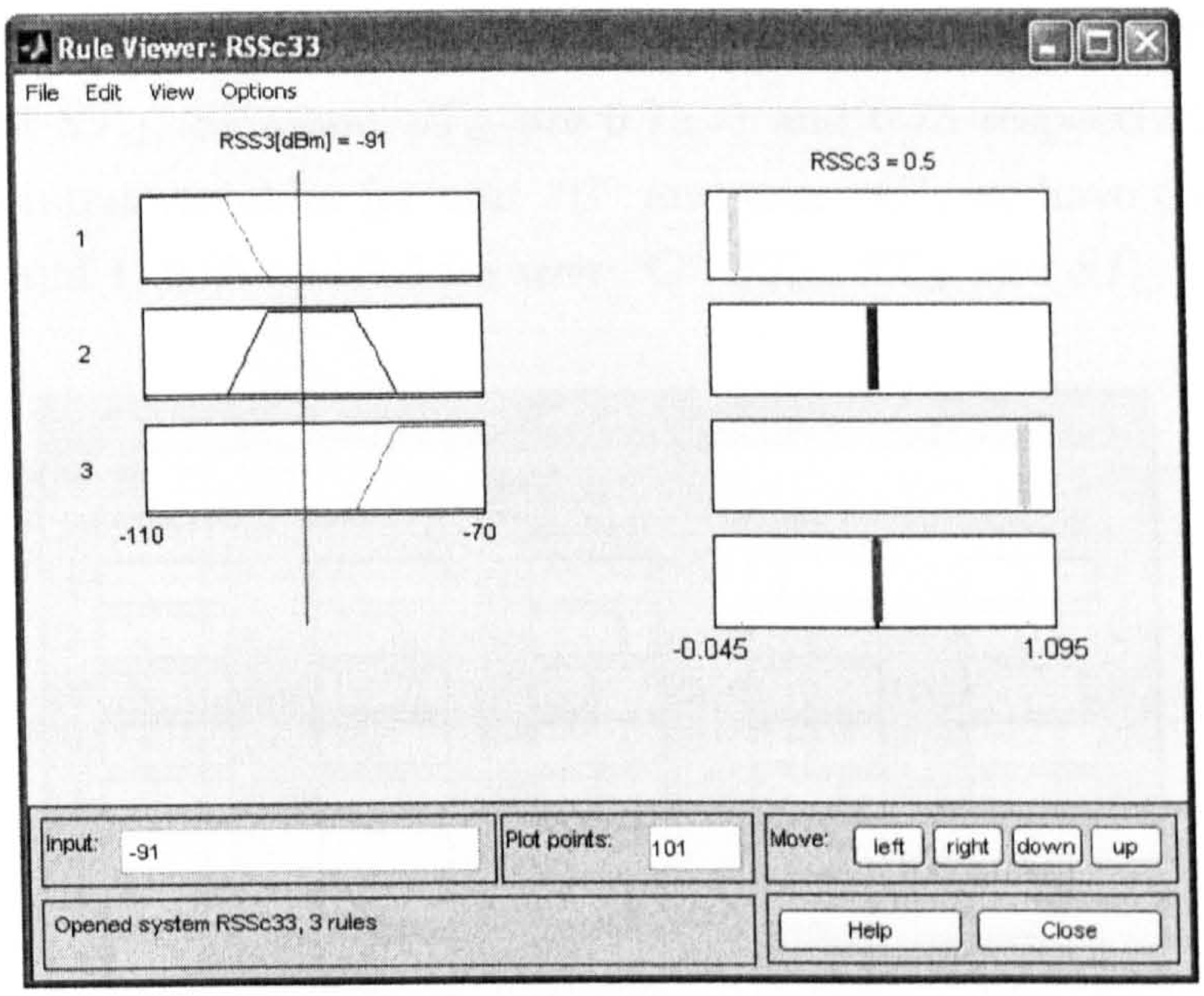

Figure 5.13: RSS_{c3} values for user "A"

shows that the values of MSS_c1, MSS_c2 and MSS_c3 are 0.5, 0.5 and 0.75 respectively. By applying the values of the MSS for user "B" and user "C", we have got 0.05, 1 and 0.25 for user "B" and 0.643, 0.357 and 0.607 for user "C" MSS_{c1}, MSS_{c2} and MSS_{c3} values.

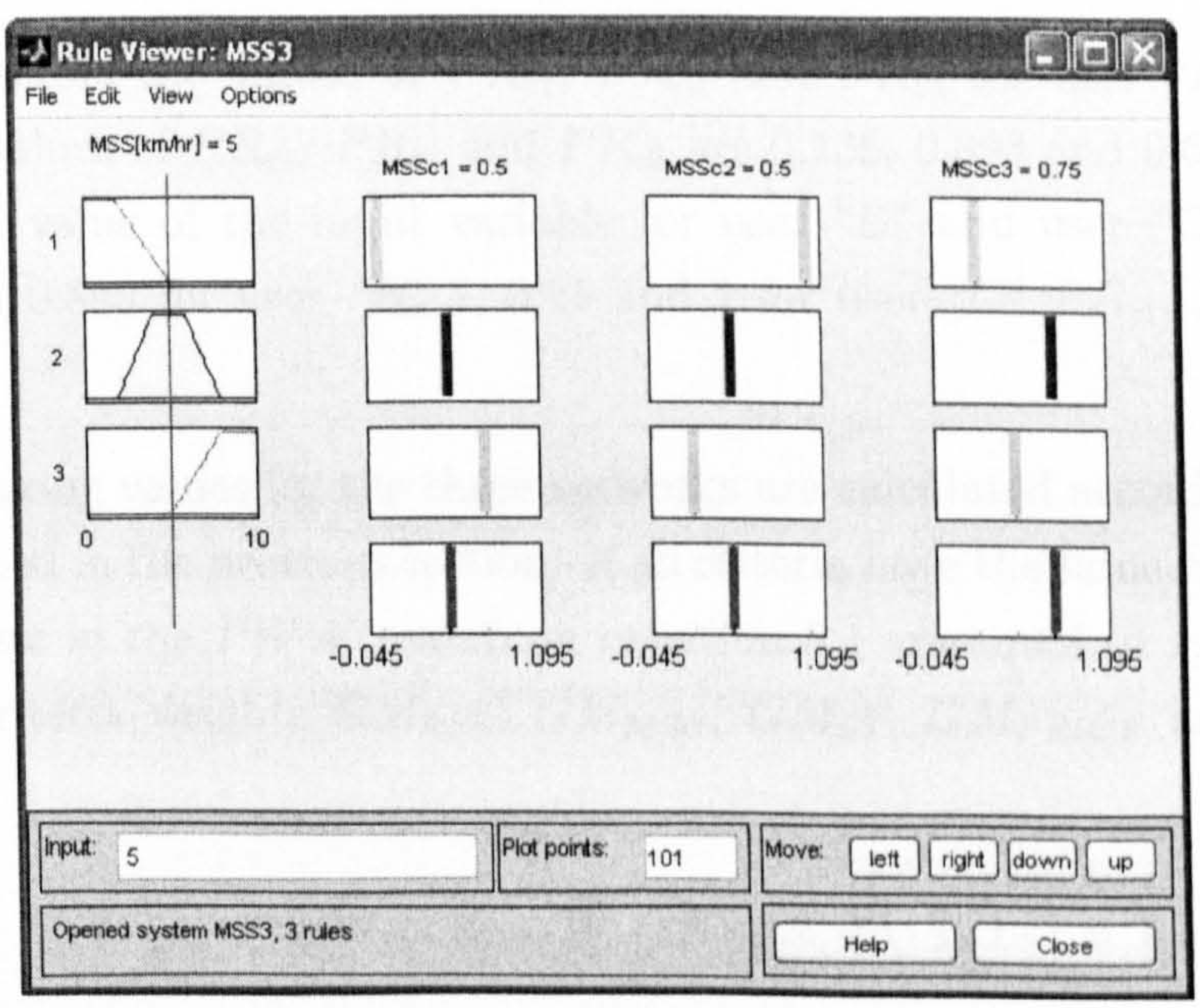

Figure 5.14: MSS_c1, MSS_c2 and MSS_c3 values for user "A"

Figure 5.15 shows the values of ST_{c1}, ST_{c2} and ST_{c3} for user "A". The figure shows that the values of ST_{c1}, ST_{c2} and ST_{c3} are 0.75, 1 and 0.75 respectively. By applying the values of the input variables for user "B" and user "C", we have got 0.25, 0.75 and 0.5 for user "B" and 1, 0.25 and 0.5 for user "C" ST_{c1}, ST_{c2} and ST_{c3} values.

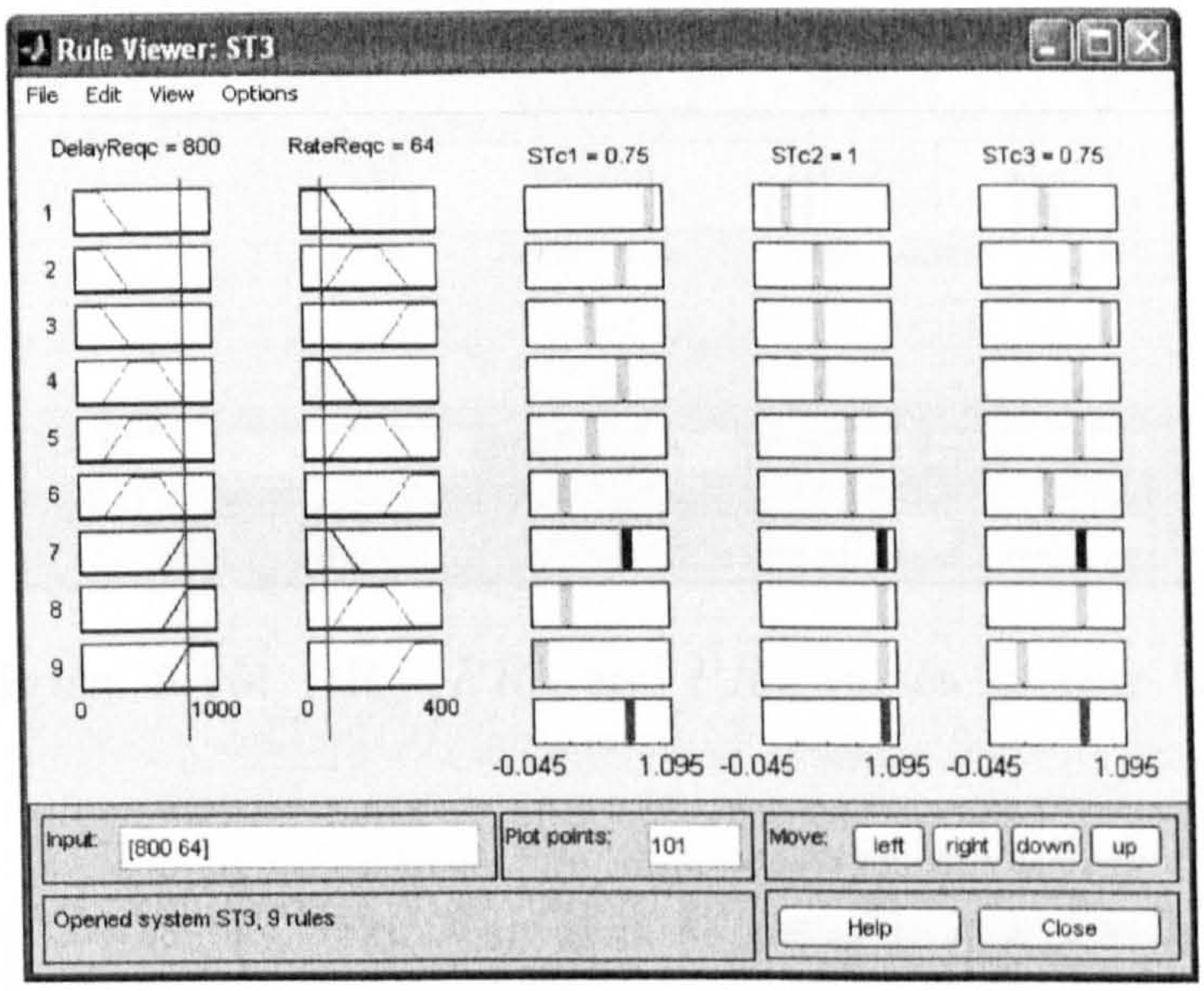

Figure 5.15: ST_{c1}, ST_{c2} and ST_{c3} values for user "A"

Figure 5.16 shows the values of PR_{c1}, PR_{c2} and PR_{c3} for user "A". The figure shows that the values of PR_{c1}, PR_{c2} and PR_{c3} are 0.136, 0.893 and 0.607 respectively. By applying the value of the input variable for user "B" and user "C", we have got 0.679, 0.464 and 0.893 for user "B" 1, 0.25 and 1 for user "C" PR_{c1}, PR_{c2} and PR_{c3} values.

The total ranking values for the three networks are calculated according to the steps that are mentioned in the previous section. If all criteria have the same importance, then all weights' values in the PWW matrix in equation 5.1 are equal to 1. The geometric means of the criteria weights GM_{RSS}, GM_{MSS}, GM_{ST}, GM_{PRICE} are calculated as follows.

$$GM_{RSS} = \sqrt[4]{W_{11} \cdot W_{12} \cdot W_{13} \cdot W_{14}} = \sqrt[4]{1 \cdot 1 \cdot 1 \cdot 1} = 1 \tag{5.24}$$

$$GM_{MSS} = \sqrt[4]{W_{21} \cdot W_{22} \cdot W_{23} \cdot W_{24}} = \sqrt[4]{1 \cdot 1 \cdot 1 \cdot 1} = 1 \tag{5.25}$$

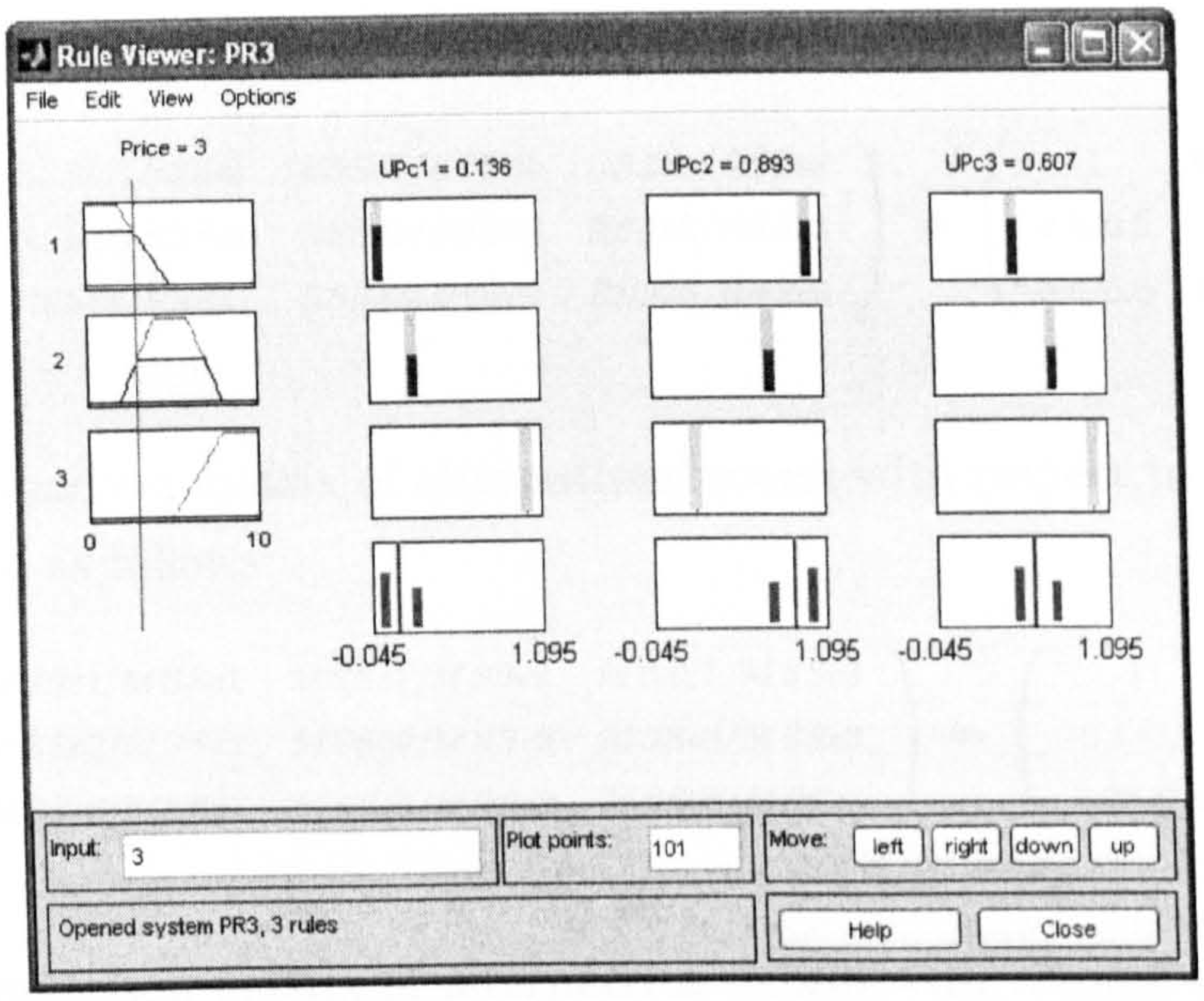

Figure 5.16: PR_{c1}, PR_{c2} and PR_{c3} values for user "A"

$$GM_{ST} = \sqrt[4]{W_{31} \cdot W_{32} \cdot W_{33} \cdot W_{34}} = \sqrt[4]{1 \cdot 1 \cdot 1 \cdot 1} = 1 \tag{5.26}$$

$$GM_{PRICE} = \sqrt[4]{W_{41} \cdot W_{42} \cdot W_{43} \cdot W_{44}} = \sqrt[4]{1 \cdot 1 \cdot 1 \cdot 1} = 1 \tag{5.27}$$

The normalized weights for the RSS, MSS, ST, and PRICE criteria NCW_{RSS}, NCW_{MSS}, NCW_{ST},and NCW_{PRICE} are calculated as follows

$$NCW_{RSS} = \frac{GM_{RSS}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} = 1/4 \tag{5.28}$$

$$NCW_{MSS} = \frac{GM_{MSS}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} = 1/4 \tag{5.29}$$

$$NCW_{ST} = \frac{GM_{ST}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} = 1/4 \tag{5.30}$$

$$NCW_{PRICE} = \frac{GM_{PRICE}}{GM_{RSS} + GM_{MSS} + GM_{ST} + GM_{PRICE}} = 1/4 \tag{5.31}$$

The pairwise comparison matrix of the alternatives' scores with respect to RSS criterion for user "A" is shown as follows:

$$PWS_{RSS} = \begin{pmatrix} RSSc1/RSSc1 & RSSc1/RSSc2 & RSSc1/RSSc3 \\ RSSc2/RSSc1 & RSSc2/RSSc2 & RSSc2/RSSc3 \\ RSSc3/RSSc1 & RSSc3/RSSc2 & RSSc3/RSSc3 \end{pmatrix} = \begin{pmatrix} 1 & 0.5/0.5 & 0.5/0.5 \\ 0.5/0.5 & 1 & 0.5/0.5 \\ 0.5/0.5 & 0.5/0.5 & 1 \end{pmatrix} \tag{5.32}$$

The pairwise comparison matrix of alternatives' scores with respect to MSS criterion for user "A" is shown as follows:

$$PWS_{MSS} = \begin{pmatrix} MSSc1/MSSc1 & MSSc1/MSSc2 & MSSc1/MSSc3 \\ MSSc2/MSSc1 & MSSc2/MSSc2 & MSSc2/MSSc3 \\ MSSc3/MSSc1 & MSSc3/MSSc2 & MSSc3/MSSc3 \end{pmatrix} = \begin{pmatrix} 1 & 0.5/0.5 & 0.5/0.75 \\ 0.5/0.5 & 1 & 0.5/0.75 \\ 0.75/0.5 & 0.75/0.5 & 1 \end{pmatrix} \tag{5.33}$$

The pairwise comparison matrix of alternatives' scores with respect to ST criterion for user "A" is shown as follows:

$$PWS_{ST} = \begin{pmatrix} STc1/STc1 & STc1/STc2 & STc1/STc3 \\ STc2/STc1 & STc2/STc2 & STc2/STc3 \\ STc3/STc1 & STc3/STc2 & STc3/STc3 \end{pmatrix} = \begin{pmatrix} 1 & 0.75/1 & 0.75/0.75 \\ 1/0.75 & 1 & 1/0.75 \\ 0.75/0.75 & 0.75/1 & 1 \end{pmatrix} \tag{5.34}$$

The pairwise comparison matrix of alternatives' scores with respect to PRICE criterion for user "A" is shown as follows:

$$PWS_{PRICE} = \begin{pmatrix} PRc1/PRc1 & PRc1/PRc2 & PRc1/PRc3 \\ PRc2/PRc1 & PRc2/PRc2 & PRc2/PRc3 \\ PRc3/PRc1 & PRc3/PRc2 & PRc3/PRc3 \end{pmatrix} = \begin{pmatrix} 1 & 0.136/0.893 & 0.136/0.607 \\ 0.893/0.136 & 1 & 0.893/0.607 \\ 0.607/0.136 & 0.607/0.893 & 1 \end{pmatrix} \tag{5.35}$$

The geometric means of the alternatives' weights $_rGM_{WWAN}$, $_rGM_{WLAN}$, and $_rGM_{WMAN}$ for user "A" with respect to RSS criterion are calculated as follows:

$$_rGM_{WWAN} = \sqrt[3]{S_{11} \cdot S_{12} \cdot S_{13}} = \sqrt[3]{1 \cdot 1 \cdot 1} = 1 \tag{5.36}$$

$$_rGM_{WLAN} = \sqrt[3]{S_{21} \cdot S_{22} \cdot S_{23}} = \sqrt[3]{1 \cdot 1 \cdot 1} = 1 \tag{5.37}$$

$$_rGM_{WMAN} = \sqrt[3]{S_{31} \cdot S_{32} \cdot S_{33}} = \sqrt[3]{1 \cdot 1 \cdot 1} = 1 \tag{5.38}$$

The geometric mean of the alternatives' weights $_mGM_{WWAN}$, $_mGM_{WLAN}$, and $_mGM_{WMAN}$

for user "A" with respect to MSS criterion are calculated as follows:

$$_{m}GM_{WWAN} = \sqrt[3]{S_{11} \cdot S_{12} \cdot S_{13}} = \sqrt[3]{1 \cdot 1 \cdot 0.5/0.75} = 0.8735 \tag{5.39}$$

$$_{m}GM_{WLAN} = \sqrt[3]{S_{21} \cdot S_{22} \cdot S_{23}} = \sqrt[3]{1 \cdot 1 \cdot 0.5/0.75} = 0.8735 \tag{5.40}$$

$$_{m}GM_{WMAN} = \sqrt[3]{S_{31} \cdot S_{32} \cdot S_{33}} = \sqrt[3]{0.75/0.5 \cdot 0.75/0.5 \cdot 1} = 1.31 \tag{5.41}$$

The geometric mean of the alternatives' weights $_{s}GM_{WWAN}$, $_{s}GM_{WLAN}$, and $_{s}GM_{WMAN}$ for user "A" with respect to ST criterion are calculated as follows:

$$_{s}GM_{WWAN} = \sqrt[3]{S_{11} \cdot S_{12} \cdot S_{13}} = \sqrt[3]{1 \cdot 0.75 \cdot 1} = 0.909 \tag{5.42}$$

$$_{s}GM_{WLAN} = \sqrt[3]{S_{21} \cdot S_{22} \cdot S_{23}} = \sqrt[3]{1/0.75 \cdot 1 \cdot 1/0.75} = 1.211 \tag{5.43}$$

$$_{s}GM_{WMAN} = \sqrt[3]{S_{31} \cdot S_{32} \cdot S_{33}} = \sqrt[3]{1 \cdot 0.75/1 \cdot 1} = 0.909 \tag{5.44}$$

The geometric means of the alternatives' weights $_{u}GM_{WWAN}$, $_{u}GM_{WLAN}$, and $_{u}GM_{WMAN}$ for user "A" with respect to PRICE criterion are calculated as follows:

$$_{u}GM_{WWAN} = \sqrt[3]{S_{11} \cdot S_{12} \cdot S_{13}} = \sqrt[3]{1 \cdot 0.136/0.893 \cdot 0.136/0.607} = 0.324 \tag{5.45}$$

$$_{u}GM_{WLAN} = \sqrt[3]{S_{21} \cdot S_{22} \cdot S_{23}} = \sqrt[3]{0.893/0.136 \cdot 1 \cdot 0.893/0.607} = 2.13 \tag{5.46}$$

$$_{u}GM_{WMAN} = \sqrt[3]{S_{31} \cdot S_{32} \cdot S_{33}} = \sqrt[3]{0.607/0.136 \cdot 0.607/0.893 \cdot 1} = 1.447 \tag{5.47}$$

Then, the normalized score of the i alternative NS_i with respect to one criterion is calculated by dividing its geometric mean by the sum of the geometric means of all alternatives as in equation 5.18. For RSS criterion $_{r}NS_{WWAN}$, $_{r}NS_{WLAN}$, and $_{r}NS_{WMAN}$

are calculated as follows:

$$_{r}NS_{WWAN} = \frac{_{r}GM_{WWAN}}{_{r}GM_{WWAN} +_{r} GM_{WMAN} +_{r} GM_{WLAN}} = 1/3 \tag{5.48}$$

$$_{r}NS_{WLAN} = \frac{_{r}GM_{WLAN}}{_{r}GM_{WWAN} +_{r} GM_{WMAN} +_{r} GM_{WLAN}} = 1/3 \tag{5.49}$$

$$_{r}NS_{WMAN} = \frac{_{r}GM_{WMAN}}{_{r}GM_{WWAN} +_{r} GM_{WMAN} +_{r} GM_{WLAN}} = 1/3 \tag{5.50}$$

For MSS criterion $_{m}NS_{WWAN}$, $_{m}NS_{WLAN}$, and $_{m}NS_{WMAN}$ are calculated as follows:

$$_{m}NS_{WWAN} = \frac{_{m}GM_{WWAN}}{_{m}GM_{WWAN} +_{m} GM_{WMAN} +_{m} GM_{WLAN}} = 0.2857 \tag{5.51}$$

$$_{m}NS_{WLAN} = \frac{_{m}GM_{WLAN}}{_{m}GM_{WWAN} +_{m} GM_{WMAN} +_{m} GM_{WLAN}} = 0.2857 \tag{5.52}$$

$$_{m}NS_{WMAN} = \frac{_{m}GM_{WMAN}}{_{m}GM_{WWAN} +_{m} GM_{WMAN} +_{m} GM_{WLAN}} = 0.429 \tag{5.53}$$

For ST criterion $_{s}NS_{WWAN}$, $_{s}NS_{WLAN}$, and $_{s}NS_{WMAN}$ are calculated as follows:

$$_{s}NS_{WWAN} = \frac{_{s}GM_{WWAN}}{_{s}GM_{WWAN} +_{s} GM_{WMAN} +_{s} GM_{WLAN}} = 0.3 \tag{5.54}$$

$$_{s}NS_{WLAN} = \frac{_{s}GM_{WLAN}}{_{s}GM_{WWAN} +_{s} GM_{WMAN} +_{s} GM_{WLAN}} = 0.4 \tag{5.55}$$

$$_{s}NS_{WMAN} = \frac{_{s}GM_{WMAN}}{_{s}GM_{WWAN} +_{s} GM_{WMAN} +_{s} GM_{WLAN}} = 0.3 \tag{5.56}$$

For PRICE criterion $_{u}NS_{WWAN}$, $_{u}NS_{WLAN}$, and $_{u}NS_{WMAN}$ are calculated as follows:

$$_{u}NS_{WWAN} = \frac{_{u}GM_{WWAN}}{_{u}GM_{WWAN} +_{u} GM_{WMAN} +_{u} GM_{WLAN}} = 0.083 \tag{5.57}$$

$$_uNS_{WLAN} = \frac{_uGM_{WLAN}}{_uGM_{WWAN} +_u GM_{WMAN} +_u GM_{WLAN}} = 0.546 \tag{5.58}$$

$$_uNS_{WMAN} = \frac{_uGM_{WMAN}}{_uGM_{WWAN} +_u GM_{WMAN} +_u GM_{WLAN}} = 0.371 \tag{5.59}$$

The total score ATS_j for alternative j is calculated according to equation 5.23. The total scores of the WWAN, WLAN, and WMAN for user "A" are 0.2315, 0.3909, and 0.358 respectively. According to the total score of all networks, the final ranking for user "A" is 1) WLAN, 2) WMAN, and 3) WWAN. The total scores and final ranking of the alternatives for users "B" and "C" can be carried out using the same process done for user "A".

5.4 Discussion

A novel operator terminal-assisted network-controlled ANS algorithm that is based on the developed framework in chapter 3 has been built in this chapter. The developed algorithm works on an HWN that contains co-existed WWAN, WLAN, and WMAN networks. It uses parallel FL and AHP MCDM tool.

Usually the ANS solutions are becoming more complex when new RATs are added. Accordingly, this chapter develops a new ANS algorithm where three RATs rather than two RATs are used. In fact, the solution can be expanded to deal with any number of RATs. The MFs of the input and output variables, the universes of discourses, and the linguistic variables remain the same. Howver, The inference rules have to be reconstructed.

Although AHP tool is more advanced than SMART tool and can give more robust and deeper insights into the selection decision making, the usage of AHP method shows much more complex calculations than SMART tool. This should be avoided when more RATs and more criteria are added. However, the number and type of the mathematical operation is still low enough to ensure real-time process.

One important problem that needs to be tackled in the two developed ANS algorithms is to find the suitable weights for the ANS criteria. The next chapter presents the usage of GA to find the suitable criteria weights that could achieve the objectives and goals of the users, operators, and QoS.

Chapter 6

Criteria Weights Optimization Using GA

One problem that needs to be tackled is the way of assigning the criteria weights on the SMART and AHP tools that are used in the operator ANS algorithms presented in chapters 4 and 5. Several optimization methods could be used to find out good or optimal values for these weights. We are not going to compare the different optimization methods that could be used and this is left for future work. This chapter presents the usage of the GA as a global heuristic search method to optimize the criteria weights in the SMART and AHP MCDM tools. The GA is used for finding the suitable weights in offline mode. GA is not used in every selection decision. It is an optional component where the operator can use it or not in offline mode prior to the selection process.

Beside its advantages over all the local optimizers that are summarized in subsection 2.5.3, our decision to use GA among the other local and global search methods was based on the nature of our objective functions that have several dynamic and stochastic components, where any other derivative-based optimization method cannot perform well. Another important issue that encouraged the selection of GA to our problem is the high interaction between different variables. At the end, in our study, the GA is not used to find an optimal solution and it is only considered as a very promising option to find good and acceptable solution.

Although the GA has proven to be a very powerful tool in many areas and application, it can perform very poor if not suitable settings for its parameters and operators that are tweaked to the considered problem are chosen. To determine good GA parameters and operators settings for our developed objective functions, several number of tests and experiments have been conducted. Based on the achieved results by the tests, the most suitable population size, crossover fraction, mutation rate, elitism account, selection function, crossover function, mutation operator for our application have been suggested.

GA is a stochastic heuristic search algorithm, which utilizes pseudo random numbers during initialization, mutation, crossover, and selection. As a consequence, two runs are never producing the same results. Therefore, statistics are needed to evaluate the performance of a GA algorithm under the different operators and parameters. To do this properly, each test needs to be repeated for several iterations while the performance is recorded. The results from all the iterations are then combined by calculating the average (and standard deviation) for each test. Usually testing GAs includes mainly two issues, how far the result obtained by GA is from the benchmark results, which can be measured by the average best fitness value achieved. The second issue is how fast GA is at finding the best solution, which can be measured by the total number of function evaluations. Since our GA is working offline, only the average best fitness value achieved by the GA is used. The average best fitness and the standard deviation are plotted against the tested parameters or against the generations. When studying a parameter all the other parameters and operators are kept constant. Some expectations about the performance of GA with respect to the second performance metric are also given.

In the following sections the main components of our GA are presented. On each section one component is discussed and several tests (if needed) are conducted to find proper setting for that component. Two functions are used for testing, ObjFun1 and ObjFun2. The structure and pseudo-code for these functions are presented on section 6.2. More functions can be tested in future work, however using the proposed two functions is thought to be enough due to the similar structure of the rest of the objective functions.

6.1 The Weights Encoding

The ANS algorithm weights W_s, W_v, W_t, and W_u of the SMART tool are encoded using real-valued numbers between 0 and 1. The length of the real-valued chromosome is 4-real floating numbers. The ANS algorithm weights W_{12}, W_{13}, W_{14}, W_{23}, W_{24}, W_{34}, of the AHP tool are encoded using real-valued numbers between 0 and 1. The length of the AHP real-valued chromosome is 6-real floating numbers. The length of each floating number is dependent on the internal precision and round-off used by the machine to define the precision of the floating numbers. The used short length of the chromosomes helps to speed up the GA convergence because a long one slows down the global search of the GA.

In our work only the real-valued representation is used and the binary representation is not a considerable option, because the weights of the SMART and AHP methods are either integer or real in nature and converting variable values to binary numbers is unnecessary. In addition, after extensive comparisons between binary and real-valued GAs, Z. Michalewicz [131] says

> "The conducted experiments indicate that the floating point representation is faster, more consistent from run to run, and provides a higher precision."

Moreover, the real-valued GA is usually faster than the binary GA, because there is no need for decoding the chromosomes prior to the evaluation of the fitness function. The real-valued GAs are easier and more compatible to combine or hybridize with other local or global optimization algorithms, since most of the optimizers use real-valued variables [125].

6.2 The Objective Functions

In this study, different objective functions are developed to cover the different and opposite objectives of the users, the QoS requirements and the operators. The developed objective functions for SMART and AHP tools are outlined in the following two subsections.

6.2.1 The SMART Tool Objective Functions

The developed objective functions for SMART tool are outlined in the following points.

1. The first objective is to maximize the percentage of users who are assigned to networks with stronger signal strength (P_q): since the solutions considers multiple criteria, they may assign a user to a network with weaker signal strength. P_q is considered as a simple indicator for performance evaluation from the QoS point of

view. To maximize P_q the objective function ObjFun1 shown in figure 6.1 is used.

```
for i ← 1 to No. of Users do
|  Net1= MSSc1*Wv + RSSc1* Ws + STc1* Wt + UPc1* Wu
|  Net2= MSSc2*Wv + RSSc2* Ws + STc2* Wt + UPc2* Wu
|  if RSSc1> RSSc2 then
|   | z=net1/net2;
|  else
|   | z=net2/net1;
|  end
|  if Z > 1 then
|   | ss=ss+1;
|  end
end
ObjFun1=ss;
```

Figure 6.1: The objective function ObjFun1

2. The second objective is to maximize the percentage of satisfied users who are assigned to a network of their preference (P_u): since the developed solutions consider multiple criteria, they may assign a user to a network different from his/her original preference. P_u is considered appropriate for performance evaluation from the user point of view. To maximize P_u the objective function ObjFun2 shown in Figure 6.2 is used.

```
for i ← 1 to No. of Users do
|  Net1= MSSc1*Wv + RSSc1* Ws + STc1* Wt + UPc1* Wu
|  Net2= MSSc2*Wv + RSSc2* Ws + STc2* Wt + UPc2* Wu
|  if UPc1> UPc2 then
|   | z=net1/net2;
|  else
|   | z=net2/net1;
|  end
|  if Z > 1 then
|   | ss=ss+1;
|  end
end
ObjFun2=ss;
```

Figure 6.2: The objective function ObjFun2

3. The third objective is to achieve higher operator benefit by saving the high cost network resources by increasing the usage of the low cost network resources. P_o

is the percentage between the number of users in WLAN to the total number of users. P_o is considered appropriate for performance evaluation from network operator point of view. To achieve this objective, the objective function ObjFun3 shown in figure 6.3 is used.

```
for i ← 1 to No. of Users do
    Net1= MSSc1*Wv + RSSc1* Ws + STc1* Wt + UPc1* Wu
    Net2= MSSc2*Wv + RSSc2* Ws + STc2* Wt + UPc2* Wu
    if Net1> Net2 then
        net1sel=net1sel+1;
    else
        net2sel=net2sel+1;
    end
end
ObjFun3=net1sel/net2sel;
```

Figure 6.3: The objective function ObjFun3

4. The ANS problem can be considered as a multi-objective problem where the operators need to consider more than one objective at once. To achieve a multi-objective optimization using GA a simple multi-objective function that can consider any combination of the previous objectives is used. This function evaluates each objective for each individual and then score all dominated individuals lower than all non-dominated individuals. One individual dominates another if it scores lower in every objective function (i.e. minimization problem). This multi-objective function is borrowed from the Matlab GA toolbox and updated as appropriate and it is named ObjFun4.

6.2.2 The AHP Tool Objective Functions

The developed objective functions used to optimize the pair-wise comparison weights between criteria for the AHP tool are outlined in this subsection. The equation 6.1 shows the matrix of the pair-wise comparison weights between criteria.

$$PWC = \begin{pmatrix} W_{11} & W_{12} & W_{13} & W_{14} \\ W_{21} & W_{22} & W_{23} & W_{24} \\ W_{31} & W_{32} & W_{33} & W_{34} \\ W_{41} & W_{42} & W_{43} & W_{44} \end{pmatrix} \tag{6.1}$$

```
ss=0;
w21=1/w(1);
w31=1/w(2);
w41=1/w(3);
w32=1/w(4);
w42=1/w(5);
w43=1/w(6);
pro11=w11* w(1)*w(2)*w(3);
pro22=w21*w22*w(4)*w(5);
pro33=w31*w32*w33*w(6);
pro44=w41*w42*w43*w44 ;
GM1 = nthroot(pro11, 4);
GM2 = nthroot(pro22, 4);
GM3 = nthroot(pro33, 4);
GM4 = nthroot(pro44, 4);
TGM= GM1+GM2+GM3+GM4;
wrss= GM1/TGM;
wmss= GM2/TGM;
wst= GM3/TGM;
wup= GM4/TGM;
for i ← 1 to No. of Users do
|   Net1= MSSc1*Wv + RSSc1* Ws + STc1* Wt +
|   UPc1* Wu
|   Net2= MSSc2*Wv + RSSc2* Ws + STc2* Wt +
|   UPc2* Wu
|   Net3= MSSc3*Wv + RSSc3* Ws + STc3* Wt +
|   UPc3* Wu
|   if (RSSc1(mm)> RSSc2(mm)) AND (RSSc1(mm)>
|   RSSc3(mm)) then
|    |  z=(net2+net3)/net1;
|   end
|   if (RSSc2(mm)> RSSc1(mm)) AND (RSSc2(mm)>
|   RSSc3(mm)) then
|    |  z=(net1+net3)/net2;
|   end
|   if (RSSc3(mm)> RSSc1(mm)) AND (RSSc3(mm)>
|   RSSc2(mm)) then
|    |  z=(net1+net2)/net3;
|   end
|   if Z > 1 then
|    |  ss=ss+1;
|   end
end
AHP3RATObjFun1=ss;
```

```
ss=0;
w21=1/w(1);
w31=1/w(2);
w41=1/w(3);
w32=1/w(4);
w42=1/w(5);
w43=1/w(6);
pro11=w11* w(1)*w(2)*w(3);
pro22=w21*w22*w(4)*w(5);
pro33=w31*w32*w33*w(6);
pro44=w41*w42*w43*w44 ;
GM1 = nthroot(pro11, 4);
GM2 = nthroot(pro22, 4);
GM3 = nthroot(pro33, 4);
GM4 = nthroot(pro44, 4);
TGM= GM1+GM2+GM3+GM4;
wrss= GM1/TGM;
wmss= GM2/TGM;
wst= GM3/TGM;
wup= GM4/TGM;
for i ← 1 to No. of Users do
|   Net1= MSSc1*Wv + RSSc1* Ws + STc1* Wt +
|   UPc1* Wu
|   Net2= MSSc2*Wv + RSSc2* Ws + STc2* Wt +
|   UPc2* Wu
|   Net3= MSSc3*Wv + RSSc3* Ws + STc3* Wt +
|   UPc3* Wu
|   if (UPc1(mm)> UPc2(mm)) AND (UPc1(mm)>
|   UPc3(mm)) then
|    |  z=(net2+net3)/net1;
|   end
|   if (UPc2(mm)> UPc1(mm)) AND (UPc2(mm)>
|   UPc3(mm)) then
|    |  z=(net1+net3)/net2;
|   end
|   if (UPc3(mm)> UPc1(mm)) AND (UPc3(mm)>
|   UPc2(mm)) then
|    |  z=(net1+net2)/net3;
|   end
|   if Z > 1 then
|    |  ss=ss+1;
|   end
end
AHP3RATObjFun2=ss;
```

Figure 6.4: The objective functions AHP3RATObjFun1 and AHP3RATObjFun2

The weights W_{11}, W_{22}, W_{33}, and W_{44} are equal to 1. For the other weights' values $W_{ij} = 1/W_{ji}$. Hence, the weights that need to be considered are reduced to six weights' values which are W_{12}, W_{13}, W_{14}, W_{23}, W_{24}, and W_{34}. The same objectives stated for SMART tool are considered for AHP tool. The developed functions have the same idea and methodology of the previous SMART functions. The developed objective functions for AHP tool are outlined in the following points.

1. The first objective is to maximize the percentage of users assigned to networks with stronger signal strength (P_q) using the objective function AHP3RATObjFun1 shown in the left part of figure 6.4.

2. The second objective is to maximize the percentage of satisfied users who are assigned to a network of their preference (P_u) using the objective function AHP3RATObjFun2

shown in the right part of figure 6.4.

3. The third objective is to achieve higher operator benefit by saving the usage of the high cost network resources (i.e. WWAN and WMAN). This objective is achieved using the objective function AHP3RATObjFun3 shown in figure 6.5.

4. The forth function is the same simple multi-objective optimization function that has been considered for SMART tool and that could consider any combination of the above three objectives.

The above objective functions are descriptive and not written in compact mathematical forms. However, the most important criteria that have been considered when designing the objective functions is that they perfectly represent the desired objectives. It is worth mentioning that the above objective functions suffer from the changing cost surface and non-smooth landscape due to the dynamic components (e.g. RSS_{c1}, UP_{c2}, etc) that are included and that could not be avoided in the objective functions. All the desired objectives are achieved by minimizing the objective functions. The global minimum value for the objective functions is zero in all cases.

6.3 The Constraints

Most optimization problems require constraints or variable bounds to deal with any unfeasible solutions that may appear outside the feasible solution space. For our problem under consideration, the constraints are needed to set upper and lower bounds on the different weights' values and to express the relationship between the variables. The number of constraints has to be as low as possible to make the search process smoother and more effective.

Different types of constraints could be applied to express the conditions that should be satisfied by the GA solution. These types include the Linear Equalities (LE), Linear Inequalities (LI), Non-linear Equalities (NE), and Non-linear Inequalities (NI).

6.3.1 SMART Weights Constraints

The assigned weights for the SMART MCDM tool have to be positive numbers because negative values have no meaningful value. Any weight minimum value is set to 0.1 in

```
ss=0;
w21=1/w(1);
w31=1/w(2);
w41=1/w(3);
w32=1/w(4);
w42=1/w(5);
w43=1/w(6);
pro11=w11* w(1)*w(2)*w(3);
pro22=w21*w22*w(4)*w(5);
pro33=w31*w32*w33*w(6);
pro44=w41*w42*w43*w44 ;
GM1 = nthroot(pro11, 4);
GM2 = nthroot(pro22, 4);
GM3 = nthroot(pro33, 4);
GM4 = nthroot(pro44, 4);
TGM= GM1+GM2+GM3+GM4;
wrss= GM1/TGM;
wmss= GM2/TGM;
wst= GM3/TGM;
wup= GM4/TGM;
for i ← 1 to No. of Users do
  | Net1= MSSc1*Wv + RSSc1* Ws + STc1* Wt +
  | UPc1* Wu
  | Net2= MSSc2*Wv + RSSc2* Ws + STc2* Wt +
  | UPc2* Wu
  | Net3= MSSc3*Wv + RSSc3* Ws + STc3* Wt +
  | UPc3* Wu
  | if (net1> net2) AND (net1> net3) then
  |   | net1sel=net1sel+1;
  | end
  | if (net2> net1) AND (net2> net3) then
  |   | net2sel=net2sel+1;
  | end
  | if (net3> net1) AND (net3> net2) then
  |   | net3sel=net3sel+1;
  | end
end
AHP3RATObjFun3=net1sel/netsel2+netsel3;
```

Figure 6.5: The objective function AHP3RATObjFun3

order to guarantee that no criterion has been totally ignored or underestimated. The weight maximum value is set to 1. To take the above conditions into account, the weights' values are subject to the two bound constrains LB and UB. Lower bounds LB = [0.1 0.1 0.1 0.1] and Upper bounds UB = [1 1 1 1]. The condition of the total summation of the weights is not applied.

6.3.2 AHP Weights Constraints

Again, the weights' values have to be positive numbers. The original AHP tool uses integer numbers between 0 and 9 for the pairwise weights. However, these specific values have not been chosen based on any theoretical foundation and they have been selected in this way to help the user to assign the weights in easy and user friendly manner. Using other values do not affect the original tool because the most important aspect in the AHP tool is the pairwise comparison concept regardless of the weights type. As a result, the real-valued representation is used.

Important conditions that have to be considered to ensure proper working of the AHP tool is to a) ensure that W_{11}, W_{22}, W_{33}, and W_{44} equal to 1 and b) ensure that usually the weight values W_{ij} is usually equal to $1/W_{ji}$. Rather than using complex constraints to consider these conditions, these conditions are involved in the design of the objective functions.

The LB constraint is used to ensure that no criterion is totally neglected or assigned negative value. LB = [0.1 0.1 0.1 0.1 0.1 0.1]. The UB constraint has not been applied, since it will complicate the cost surface.

6.4 The Population Settings

The uniform creation function is used to create the initial population. This function creates a random initial population with a uniform distribution. The initial range of weights is set to the range of [0.1 1]. The population size determines the size of the population at each generation. The population size has a significant impact on the ability of the GA to find an acceptable minimum. Consequently, several tests are presented here to find out the most suitable population size for our application.

In figure 6.6, the lower plot shows the mean and standard deviations of the ObjFun1 best fitness values over 20 runs, for each of the values of the population sizes 10, 30, 50, 70, and 90. The upper plot shows a colour-coded display of the best fitness values in each run. For ObjFun1 fitness function, setting population size to 30, 50, or 70 yields the best results. However, a different setting for population size yields comparable results.

In figure 6.7 the lower plot shows the means and standard deviations of the ObjFun2

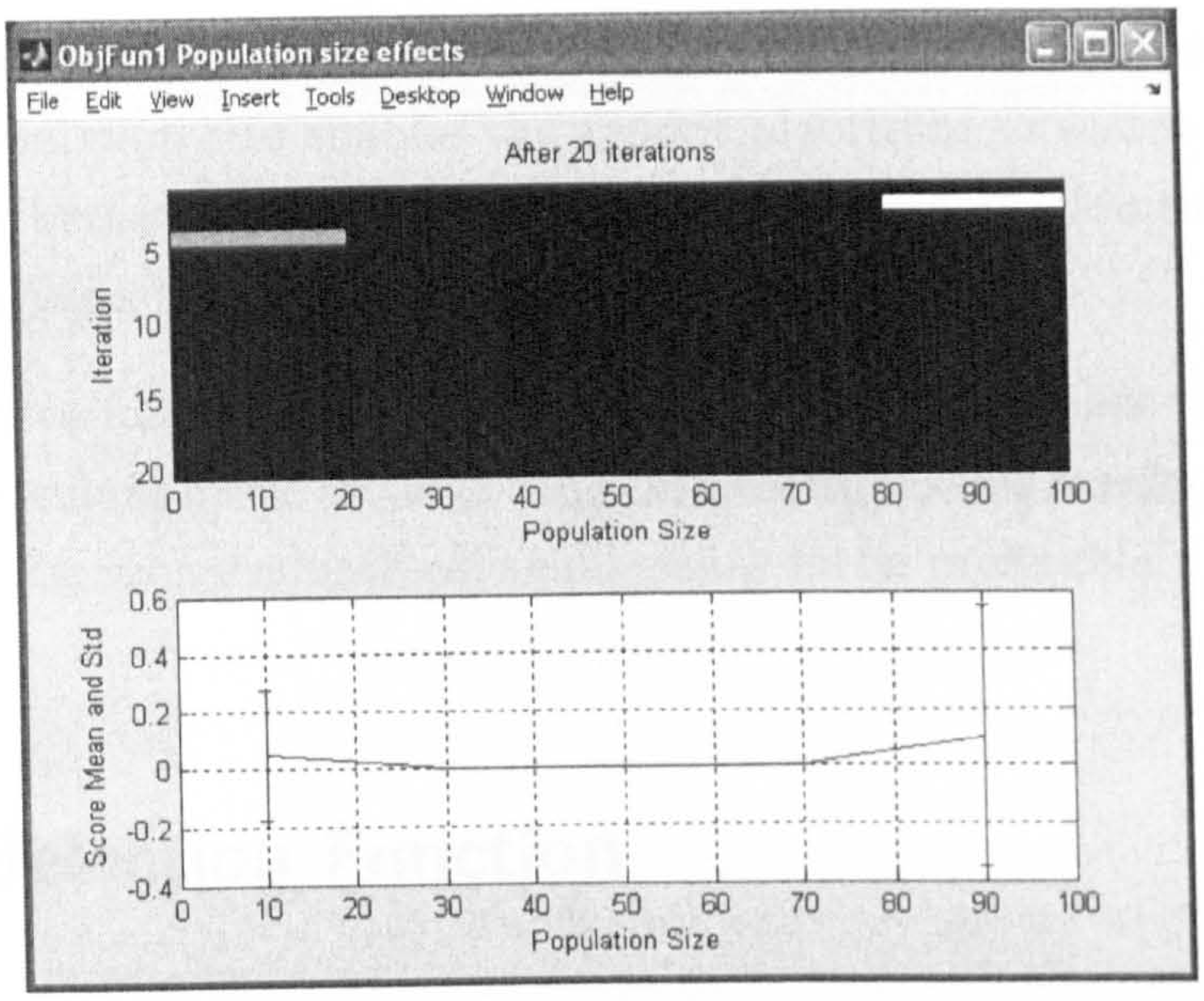

Figure 6.6: The effect of population size on the objective function ObjFun1

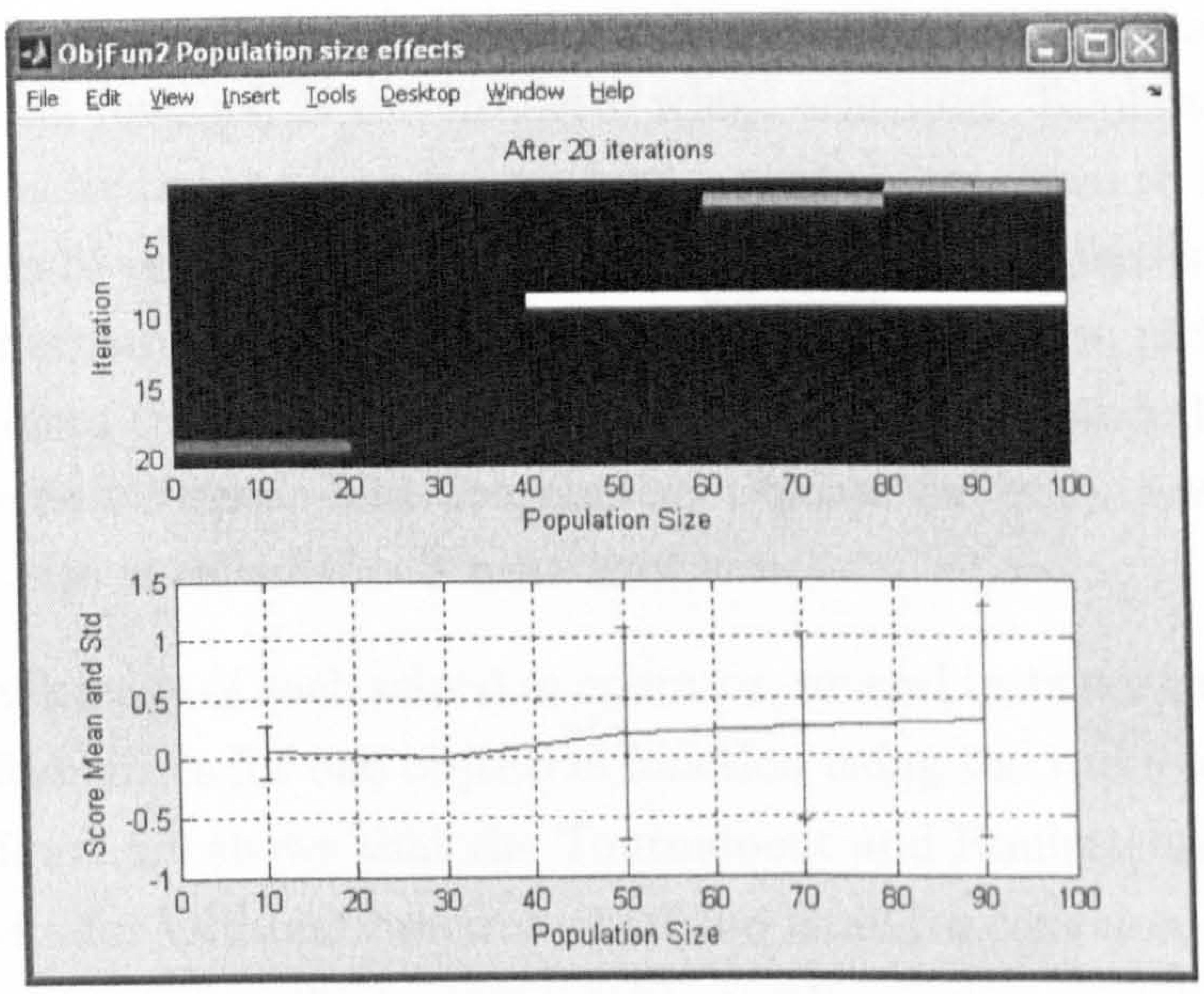

Figure 6.7: The effect of population size on objective function ObjFun2

best fitness values over 20 runs, for each of the values of the population sizes 10, 30, 50, 70, and 90. For ObjFun2 fitness function, setting population size to 30 yields the best result. However, setting the population size for a lower value yields comparable results.

It is clearly noticeable that the optimal population size is dependent on the fitness function. There are not exact values that could be recommended for all objective functions. However general recommendations can be given to set the population size. Increasing the population size enables the genetic algorithm to search more points and thereby it obtains better result. However, the larger the population size, the longer the genetic algorithm takes to compute each generation.

For our objective functions and with respect to the best fitness value metric, both large and small population size settings can achieve comparable results, but with respect to the number of function evaluations, small size is much preferable.

6.5 The Selection Function

Three different selection functions are compared to pick up one. The first selection function is the Uniform selection function. Uniform function selects parents randomly using a uniform distribution that is based on the expectations and number of parents. The second selection function is the Roulette wheel selection. Roulette wheel selection picks a particular individual to be a parent with a probability equal to its fitness divided by the total fitness of the population. The third selection function is the Tournament selection with a tournament size equals to 4. Tournament selection picks a subset of the population at random (in our case 4 individuals in the subset), and then, it selects the member with the best fitness. The tournament repeats for every parent needed. The size of the subset size is called the Tournament size.

To study the efficiency of each selection operator, several tests are carried out. In each test, the GA performances for one objective function using the three selection operators are compared. Figure 6.8 shows that the Tournament and Roulette selections achieve a slight better results for Objfun1 function than the Uniform selection. Figure 6.9 shows that all the three operators achieve comparable results.

Each of the parent selection schemes results in a different set of parents. As such, the composition of the next generation is different for each selection operator. However it is clear that there is no big difference between the best fitness values achieved by the different operators, which means that the type of the selection operator does not have a big impact on the GA work. It is very difficult to give advice on which selection operator works best. However, Roulette wheel and Tournament selection are de-facto standard and widely used for most GAs. Generally speaking that Tournament selection works better for larger population sizes in terms of convergence time because sorting used by other selection operators becomes time-consuming for large populations.

6.6 The Elitism Count

To ensure elitism, the number of individuals that are guaranteed to survive to the next generation is usually set to a certain value called elitism count. To study the effects of the elitism count on the GA performance, the population size has been set to 20 individuals and the elitism count has been increased from 0 to 20 with step size equals to 2.

In Figure 6.10, the lower plot shows the means and standard deviations of the ObjFun1 best fitness values over 20 runs, for each of the values of the elitism count 2, 4, 6, 8, 10, 12, 14, 16, and 18. The upper plot shows a colour-coded display of the best fitness values in each run. For ObjFun1 fitness function, setting elitism count to lower values yields better and fixed results and setting the elitism count to higher values yields worse results.

In Figure 6.11, the lower plot shows the means and standard deviations of the ObjFun2 best fitness values over 20 runs, for each of the values of the elitism count 2, 4, 6, 8, 10, 12, 14, 16, and 18. For ObjFun2 fitness function, setting elitism count to 8 or 10 yields the best result. Because of the non-smooth and stochastic nature of the objective

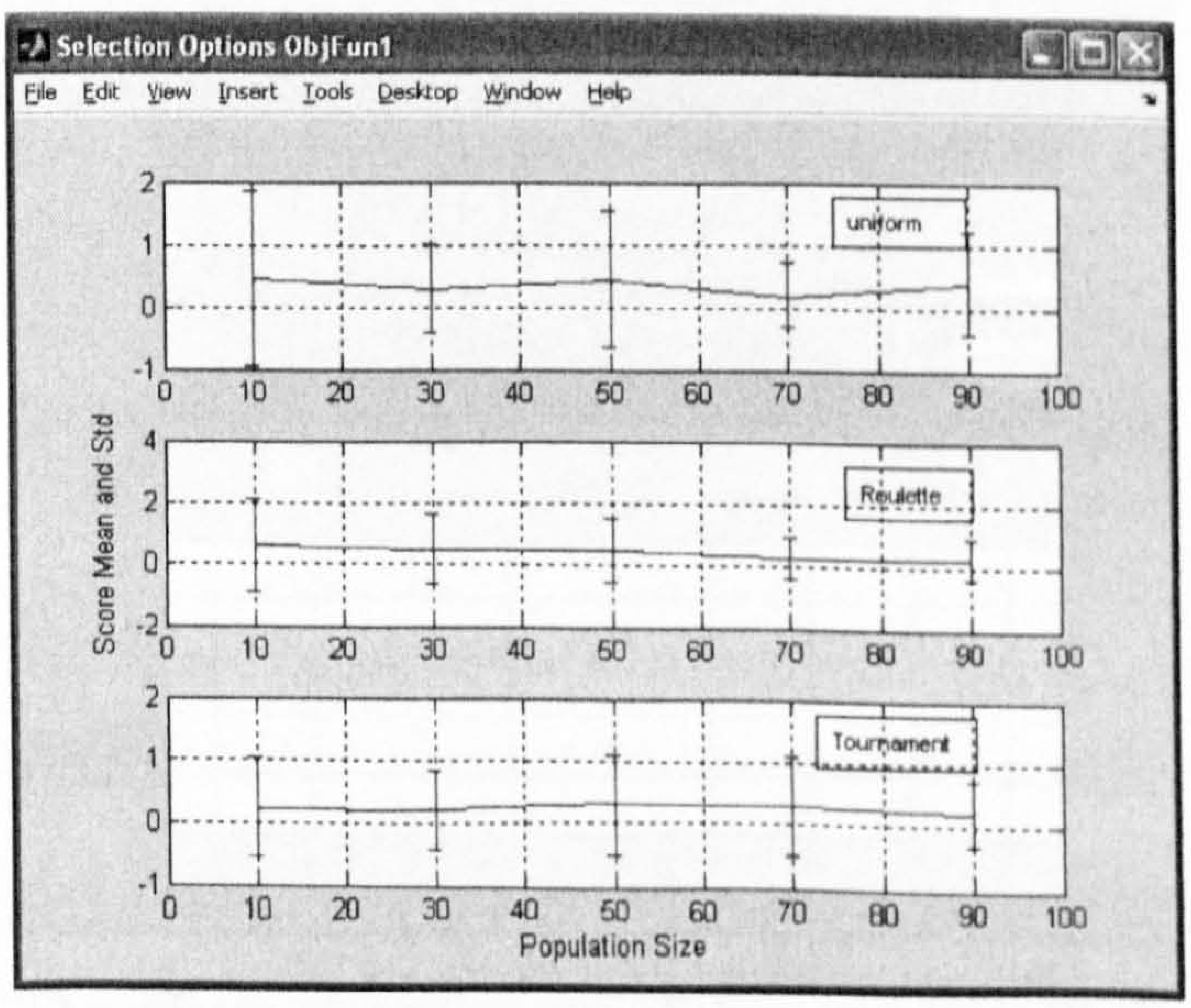

Figure 6.8: ObjFun1 best fitness values with the different selection operators

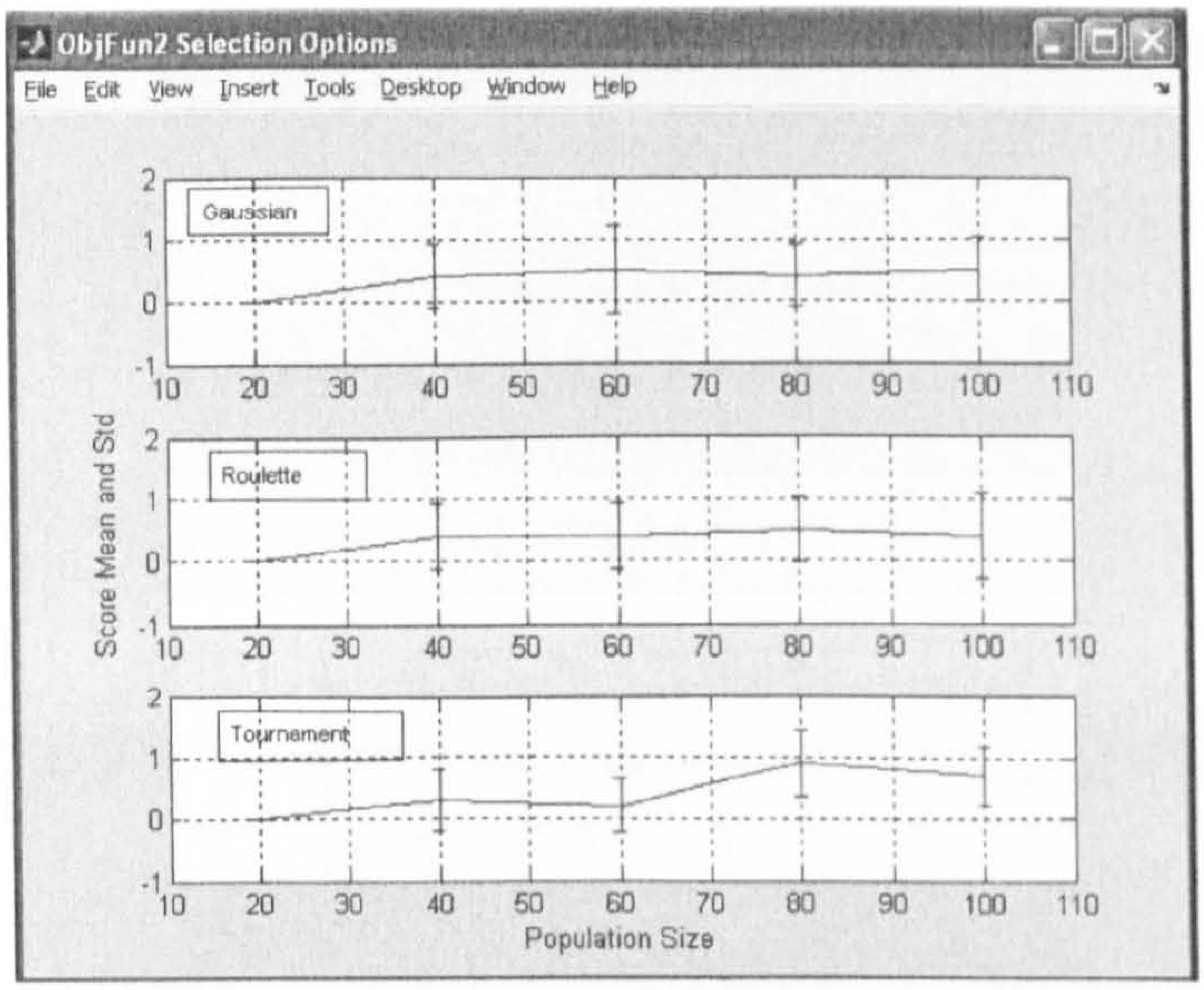

Figure 6.9: ObjFun2 best fitness values with the different selection operators

function, no general recommendations can be given except that very high elite count should be avoided to allow more time for exploration by GA.

Deciding how many elite chromosomes to keep to the next generation is somewhat arbitrary and highly dependent on the objective function. There are not exact values that could be recommended for all objective functions. If the elite fraction is defined to

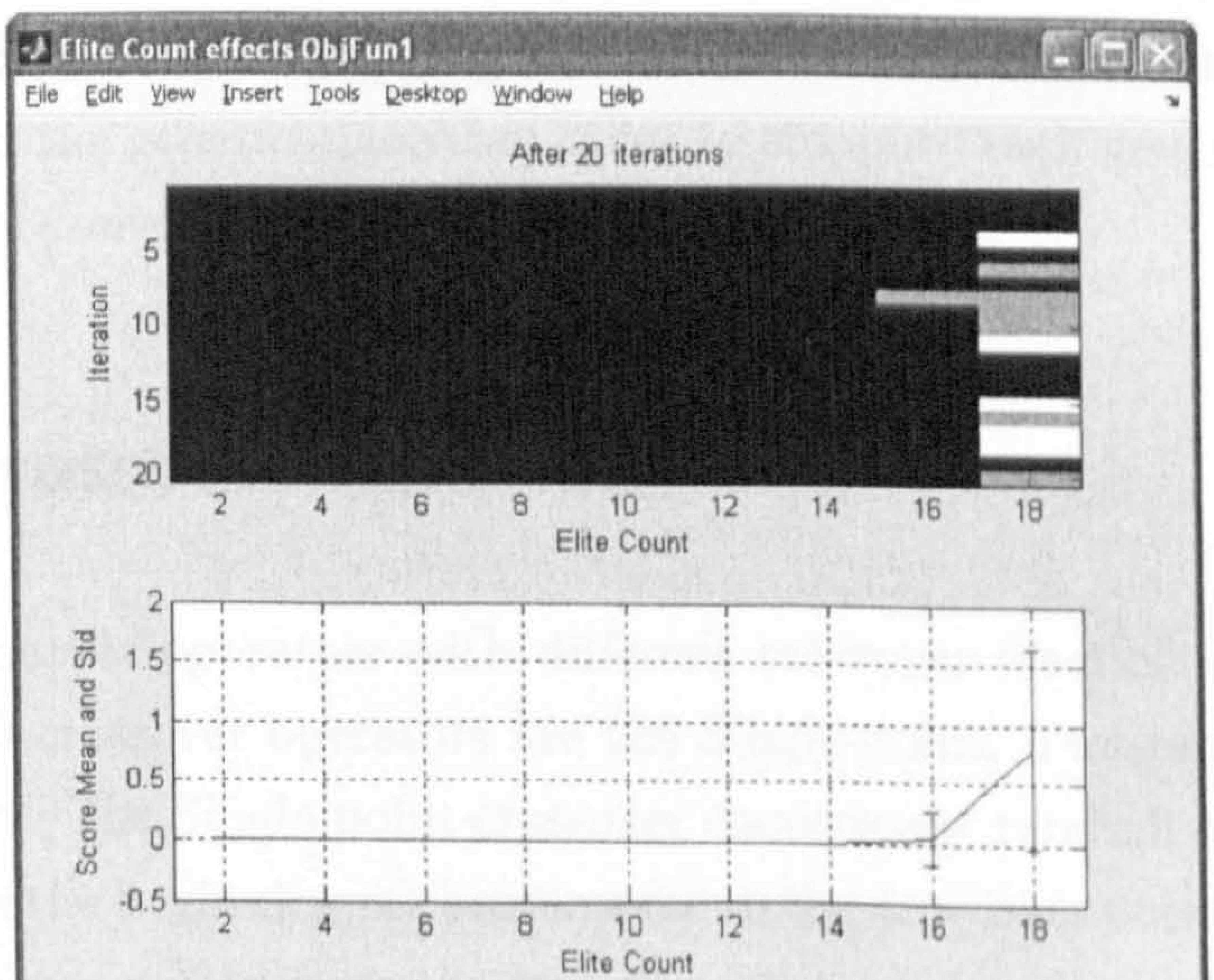

Figure 6.10: The affects of varying the elitism count on ObjFun1 best fitness values

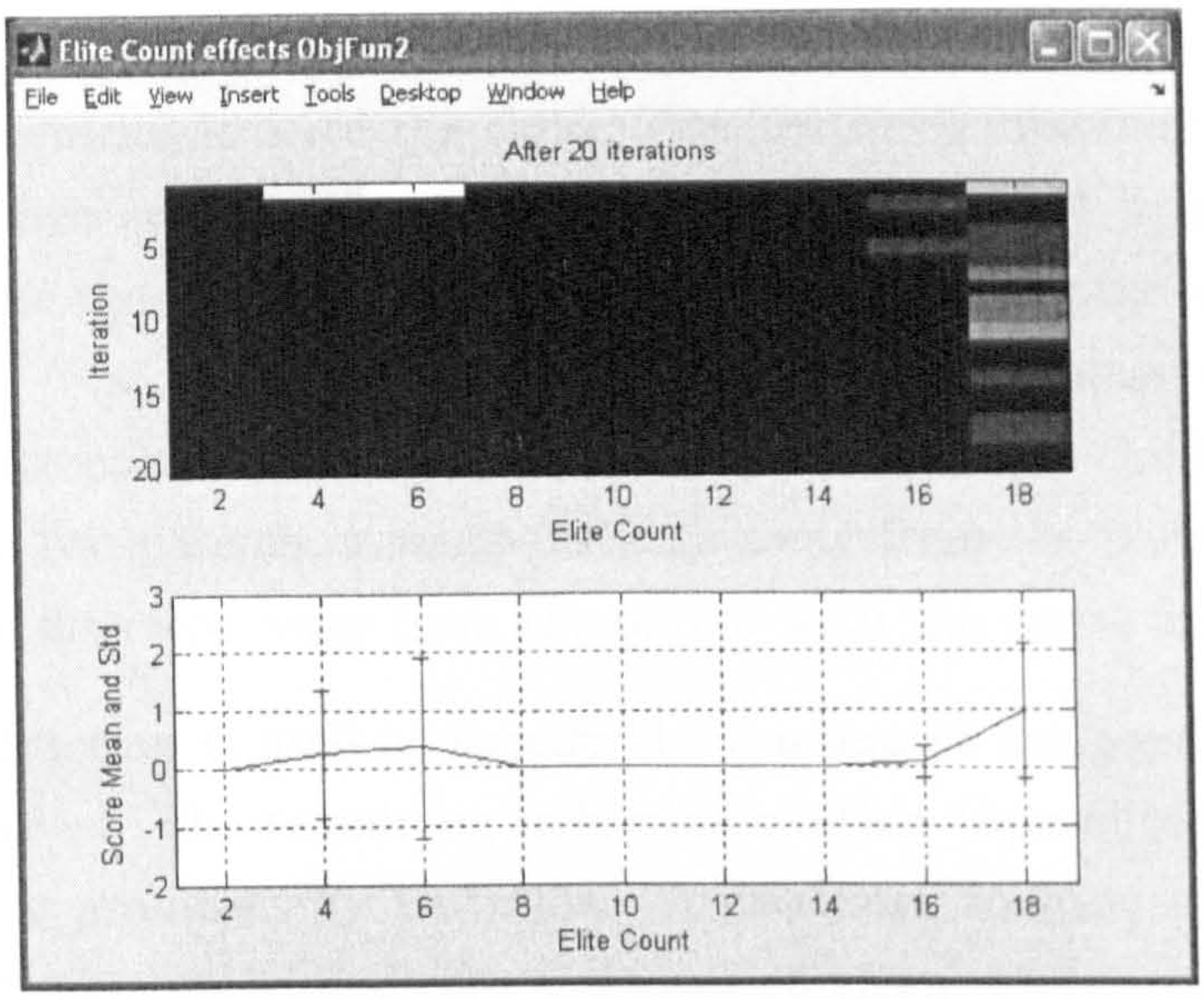

Figure 6.11: The affects of varying the elitism count on ObjFun2 best fitness values

be the percentage of the elite count to the population size then, it is highly recommended to set this fraction to value more than 0, because this can guarantee to some extent that the best fitness value can only decrease from one generation to the next. This is what we want to happen, since the genetic algorithm minimizes the objective function. Setting elite count to a high value causes the fittest individuals to dominate the population and limits the crossover and mutation children, which in turn can lead to less effective search and increase the probability of trapping by local minima. However, the smaller the elite fraction, the longer the genetic algorithm takes to compute each generation and the less efficient in terms of convergence time.

6.7 The Crossover Function

Four different crossover operators with different crossover fraction settings have been tested. The tested crossover operators are the Single-point, Two-point, Scattered, and Heuristic operators. The Single-point crossover chooses one random crossover point, the vector entries from the beginning of chromosome to the crossover point is copied from the first parent, the rest is copied from the second parent, and concatenates these entries to form the child. The Two-point crossover selects randomly two random crossover points. The vector entries from the beginning of chromosome to the first crossover point is copied from the first parent, the part from the first to the second crossover point is copied from the second parent and the rest is copied again from the first parent. The function then concatenates these entries to form the child. The Scattered crossover creates a random binary vector. It then selects the genes where the vector is a 1 from the first parent, and the genes where the vector is a 0 from the second parent, and combines the genes to form the child. The Heuristic crossover uses the fitness values of the two parent chromosomes to determine the direction of the search. It creates children that lie on the line containing the two parents, a small distance away from the parent with the better fitness value in the direction away from the parent with the worse fitness value.

The crossover fraction is used to specify the fraction of the next generation that is produced by crossover. The remaining individuals, other than elite individuals, in the next generation are produced by mutation. A crossover fraction of 1 means that all children other than elite individuals are crossover children, while a crossover fraction of 0 means that all children are mutation children.

Several tests are carried out using several fitness functions with various crossover fractions and operators to study the impact of the variations on the crossover fraction on the ability of the GA to find an acceptable minimum. Figure 6.12 shows the means and standard deviations of the ObjFun1 best fitness values over 20 runs, for each of the values of the crossover fractions 0, 0.2, 0.4, 0.6, 0.8, and 1. For ObjFun1 fitness function, setting crossover fraction to 0.8 or lower yields the best result. No clear difference between the best fitness values that are achieved by the different methods is found.

Figure 6.13 shows the means and standard deviations of the ObjFun2 best fitness values over 20 runs, for each of the values of the crossover fractions 0, 0.2, 0.4, 0.6, 0.8, and 1. For ObjFun2 fitness function, setting crossover fraction to 0.8 or lower yields the best result. However, the different crossover operators achieve comparable results.

6.8 The Mutation Function

Three different mutation functions have been tested to find out the most suitable one for our GA based application. The three functions are the Uniform, the Gaussian, and the Adaptive feasible mutation functions. The Uniform mutation function selects a fraction of the vector entries of an individual for mutation, where each entry has a probability of "Mutation Rate" of being mutated. Then, it replaces each selected entry by a random

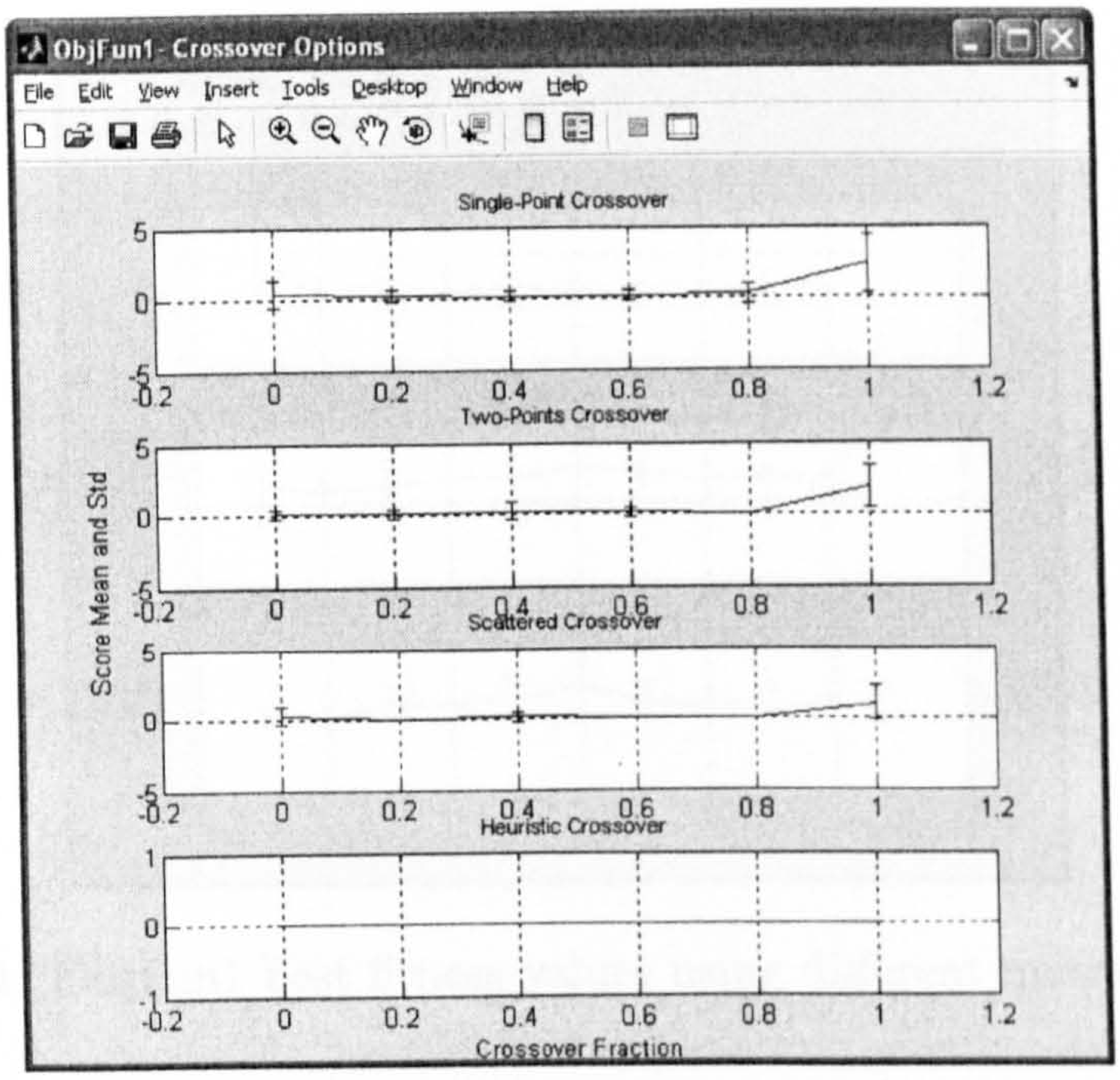

Figure 6.12: ObjFun1 best fitness values with different crossover options

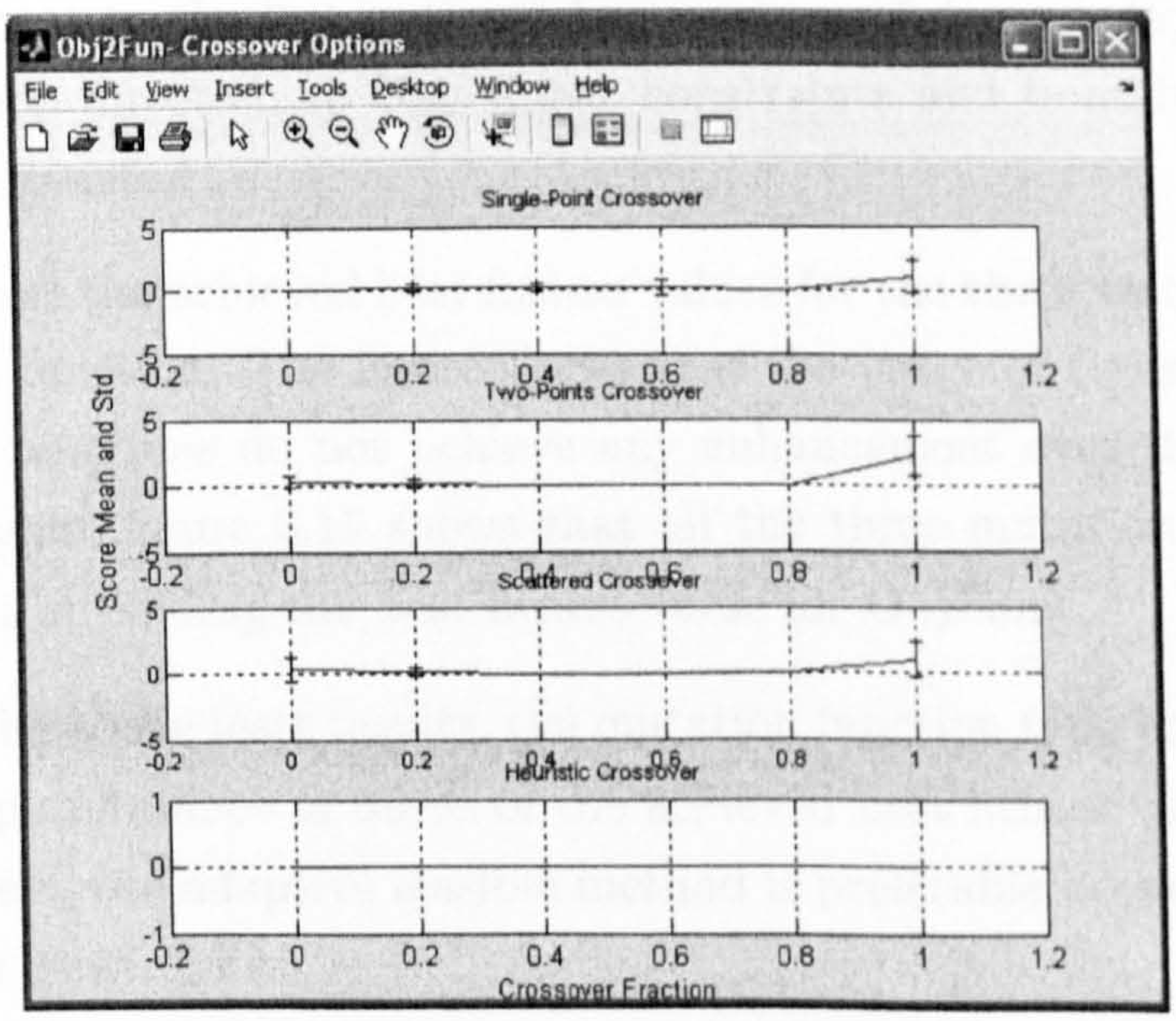

Figure 6.13: ObjFun2 best fitness values with different crossover options

number selected uniformly from a range for that entry. The Gaussian mutation function adds a random number to each element of an individual vector. This random number is taken from a Gaussian distribution centred on zero. Matlab controls the variance amount of this distribution using two parameters. The Scale parameter determines the

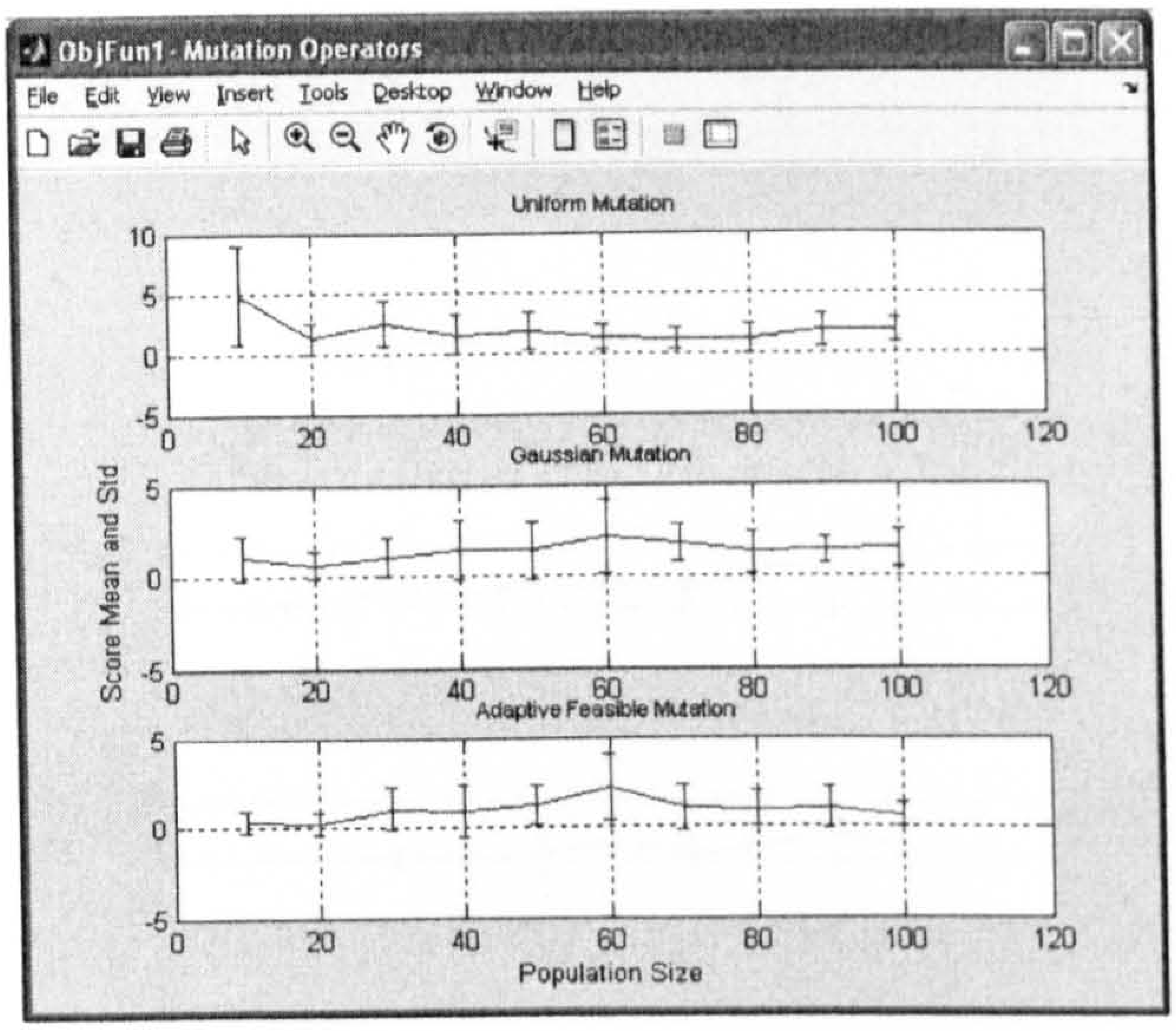

Figure 6.14: ObjFun1 best fitness values using different mutation functions

variance at the first generation. The Shrink parameter controls how variance shrinks as generations go by. Adaptive feasible mutation generates random directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along each direction so that linear constraints and bounds that specify the feasible region are satisfied.

Figure 6.14 shows the achieved best fitness values for the three tested mutation functions for ObjFun1 function. The figure shows that the usage of Gaussian and adaptive feasible mutation functions do not achieve any enhancement over the traditional uniform function. Again, figure 6.15 shows that all the three mutation functions achieve comparable results on finding the best fitness value for ObjFun2.

According to the above tests results, the mutation function type has not considerable effect on the GA performance in terms of the achieved best fitness value. However, in a constrained problem, the adaptive feasible method is preferable because it can meet the applied problem's constraints.

6.9 The Mutation Rate

The GA can converge too rapidly into one area of the objective function cost surface, while leaving many other regions that may contain other minima. As a result, the GA could end up in a local rather than a global minimum. To avoid this problem, the GA

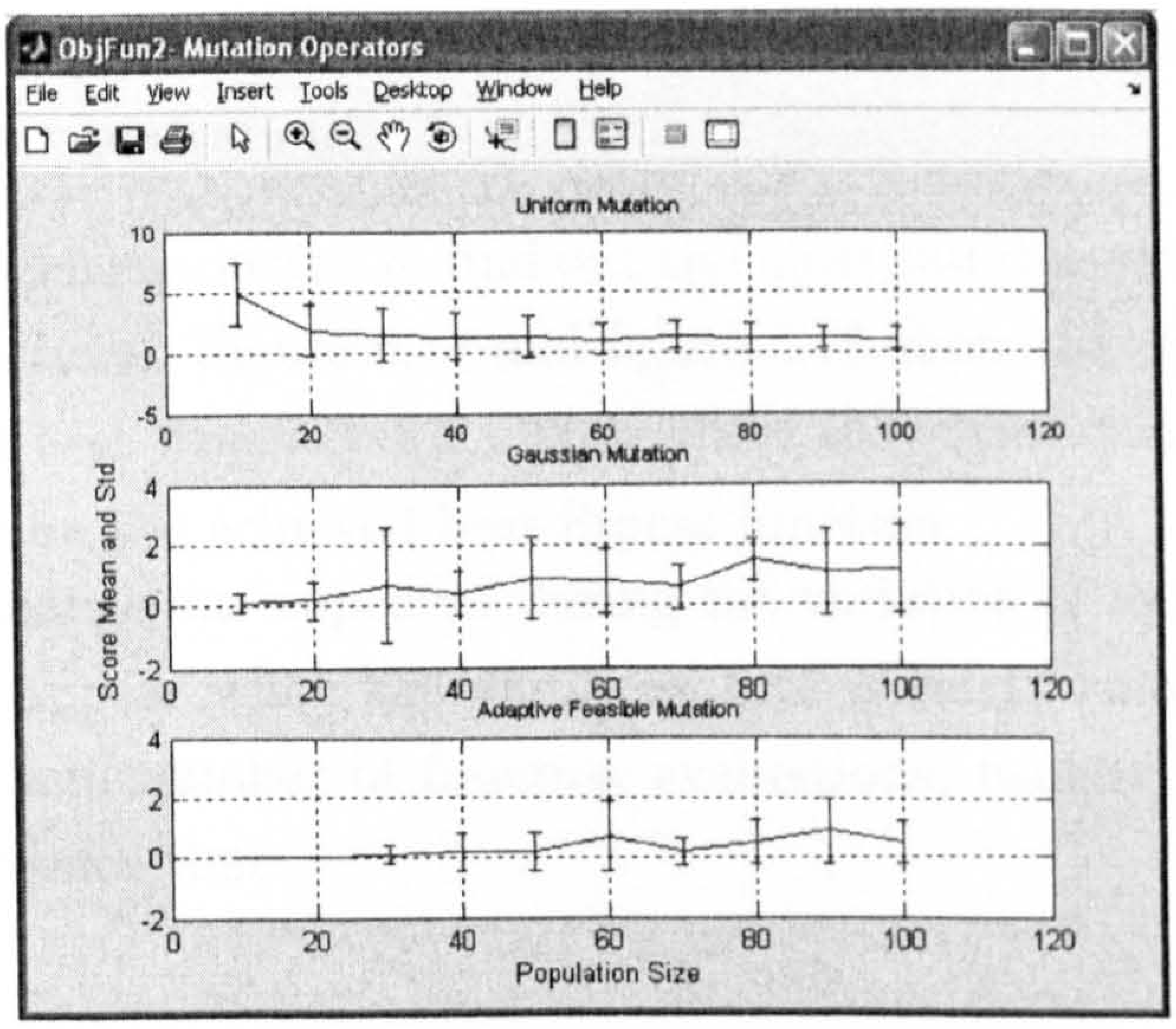

Figure 6.15: ObjFun2 best fitness values using different mutation functions

is enforced to search other areas of the cost surfaces by introducing small changes (i.e. mutations) in some of the variables. However two important issues arise here, the first issue is how these changes are applied (i.e. the mutation operator type) and the second issue is how much these changes are applied (i.e. the mutation rate). The first issue has been already discussed in the previous section and this section discusses the second issue.

The mutation rate is the percentage of bits in a population mutated each iteration of the GA. In fact the mutation rate is so important issue to be considered, because it provides and controls the genetic diversity and enables the GA to search a broader space by controlling the number of changes in the GA individuals. The diversity of the population is one of the most important factors that determine the performance of the genetic algorithm. The diversity shows the average distance between the individuals, if the average distance between individuals is large, the diversity is high; if the average distance is small, the diversity is low.

Figure 6.16 shows the effect of mutation rate on diversity for ObjFun1 as unconstrained problem. The mutation rate has been set to a variable that decreases with time. The upper plot displays the average distance between individuals in each generation. As the amount of mutation decreases, the average distance between individuals also decreases which is approximately 0 at the final generation. The lower plot displays a vertical line at each generation, showing the range from the smallest to the largest fitness value, as well as the mean fitness value. As the amount of mutation decreases, so does the range. These plots show that reducing the amount of mutation decreases the diversity of subsequent generations.

Basic tests have been conducted to find out the most suitable values of mutation rate for our objective functions. Figure 6.17 and figure 6.18 show the effect of the mutation rate on the achieved best fitness value. They show that mutation rate more than 0.1 has not a big impact on the achieved best fitness function.

In fact, a slight change has appeared during the variation of mutation rate from 0.1 to 1. Worse results appear when the mutation rate is set to smaller value. In terms of convergence time and number of function evaluations, usually lower mutation rate ensures lower convergence time.

6.10 The Stopping Criteria

The GA stops when one of the stopping criteria is met. Stopping criteria reflect that no improvement in the objective function is achieved a) during an interval of time in seconds equal to *Stall Time Limit*, b) after running the GA for X number of iterations called *Stall Generations*, or c) in the best fitness value of the current population that is less than or equal to *Fitness Limit.* If the GA does not stop for one of the reasons above, then *Time Limit* or *Generations Limit* has to be applied to limit the running time or the maximum number of iterations. Otherwise, GA can go on forever unless stopped. What is the criterion that should be used and what is the proper value that could be

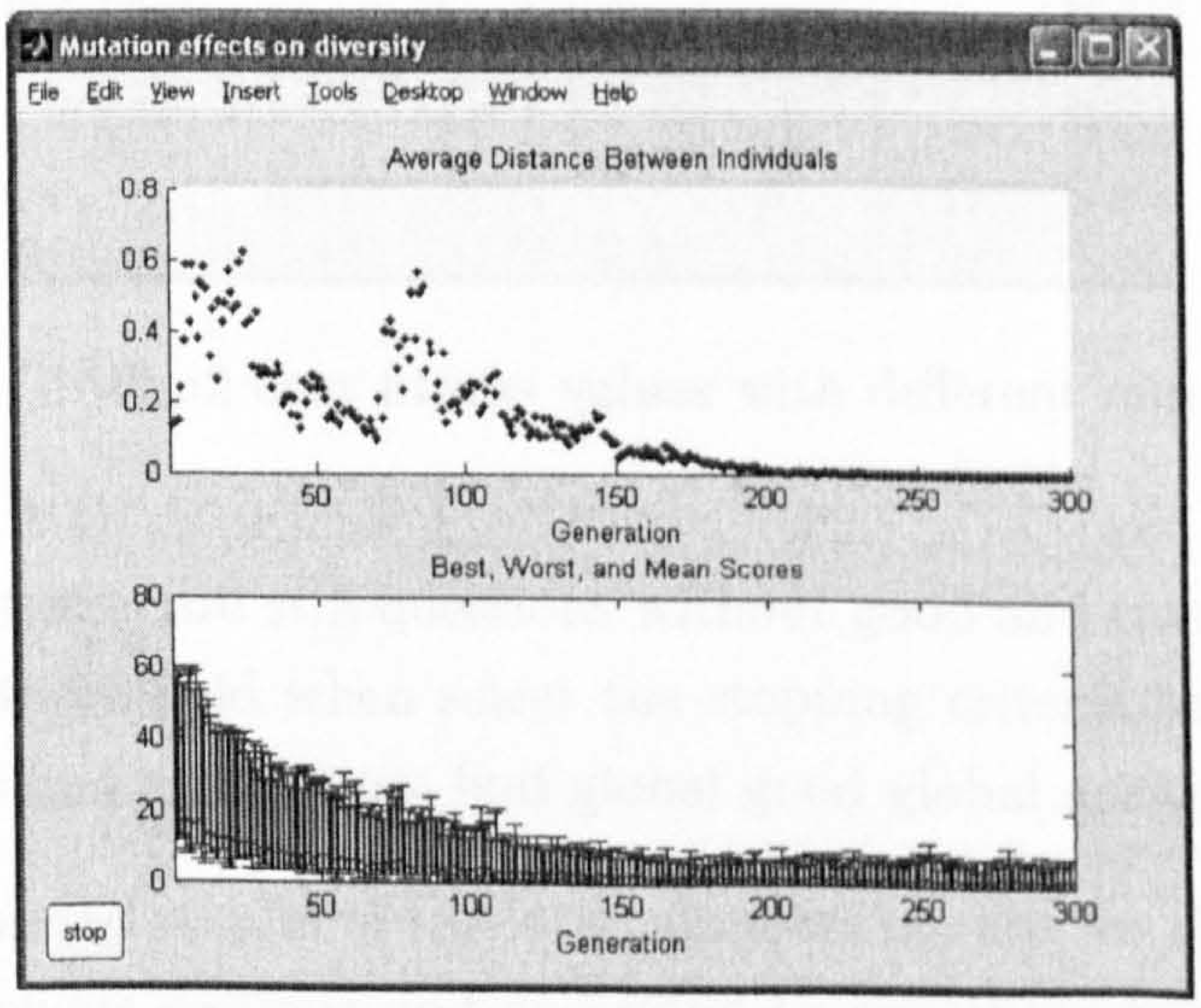

Figure 6.16: The mutation effect on GA diversity

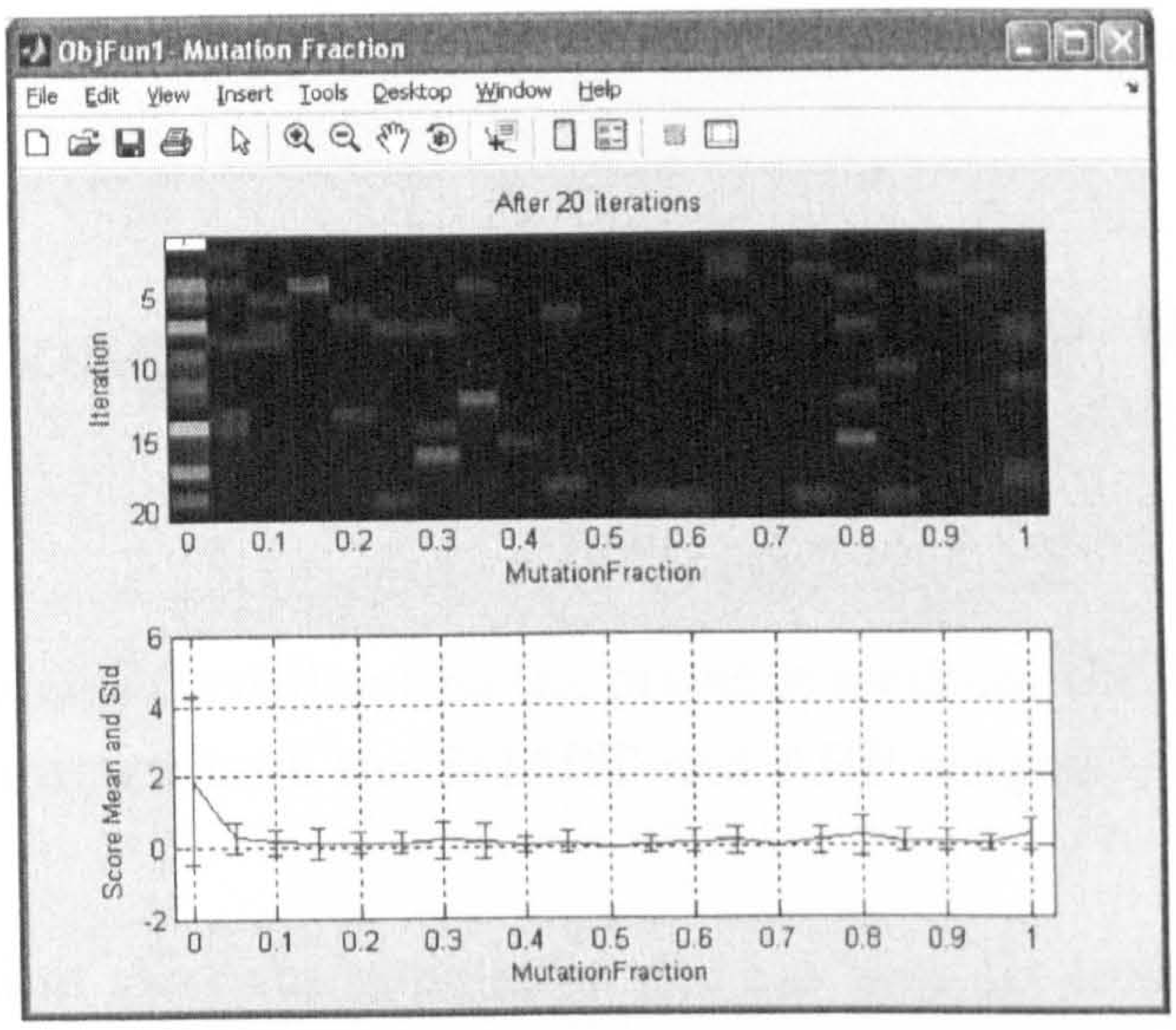

Figure 6.17: ObjFun1 best fitness values with different mutation fractions

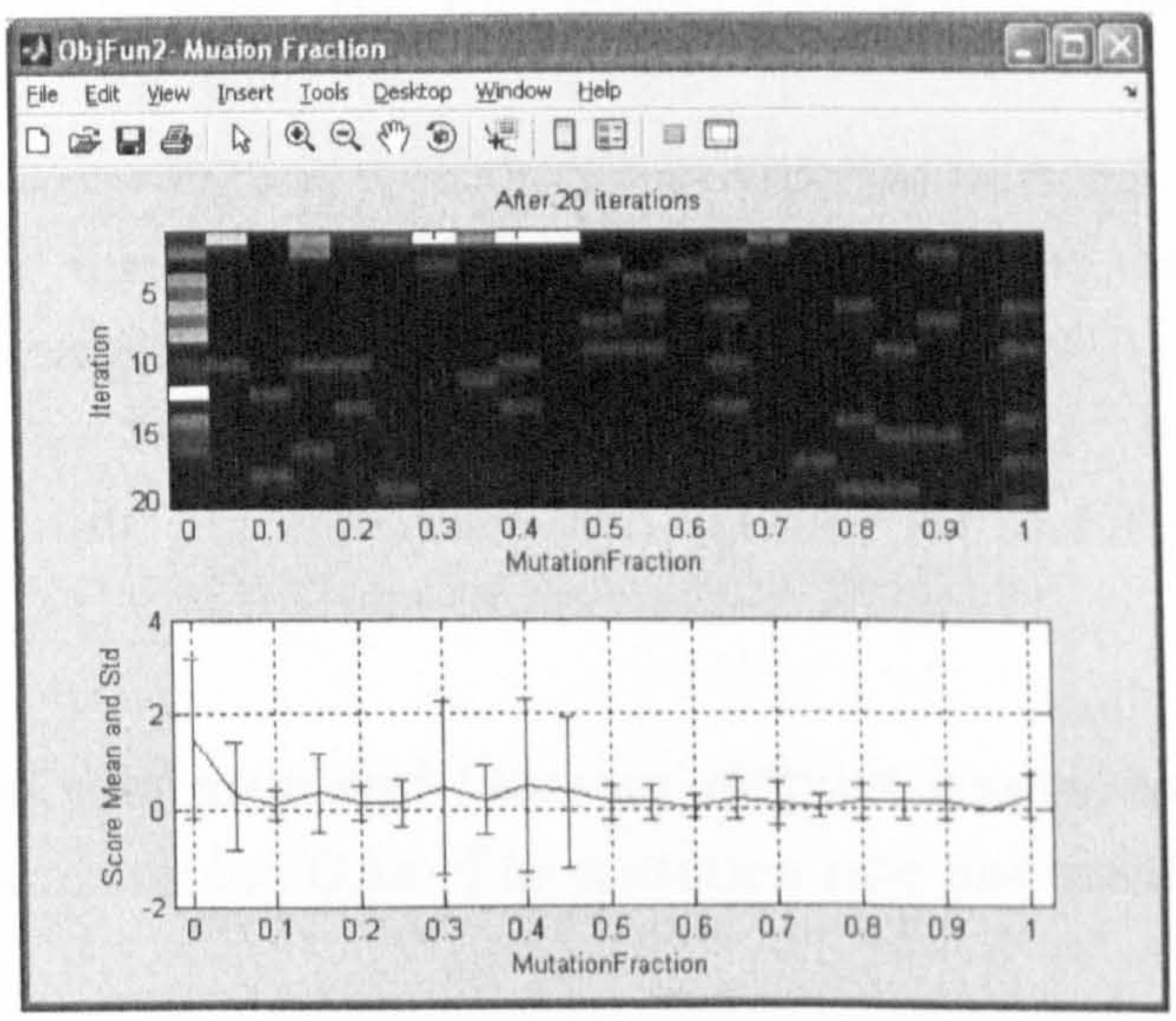

Figure 6.18: ObjFun2 best fitness values with different mutation fractions

assigned for each criterion are still questions without good and clear answers. However, more attention has to be paid when select the stopping criteria because the GA could be stuck at local minima rather than find global good global answer.

Based on the achieved results of the large numbers of runs for the different objective functions in the previous sections and according to our observations, our GAs stop if there is no improvement in the best fitness value for number of consecutive generations (i.e. *Stall Generations Limit*) equals to 50 generations or if the maximum number of the GA iterations (i.e. *Generations Limit*) reaches to 100 or 300 iterations.

6.11 Optimizing the SMART and AHP Weights using GA

Based on the experiments carried out on the previous sections, the following GA settings have been used to optimize both the SMART and AHP weights.

- **The population size**: the population size has been set to different values 20, 50, 70, and 100 individuals to check the GA convergence.
- **The selection operator**: the Tournament selection function with Tournament-size set to 4 has been used.
- **The crossover operator and fraction**: the Heuristic crossover function has been used. The crossover fraction has been set to 0.8.
- **The elitism count**: the elitism fraction has been set to 10% from the population size.
- **The mutation operator and rate**: an adaptive feasible mutation operator has been used for constrained GAs. The mutation rate has been set to 0.1.
- **The constraints**: the above mentioned constrains in section 6.3 have been applied.
- **The stopping criteria**: the *Stall Generations Limit* has been set to 50 Generations. The *Generations Limit* has been set to 100-300 generations. The other stopping criteria have been set to either Inf or -Inf.

For every objective function, the GA has been run to determine the best weights' values in terms of the best fitness value achieved. The runs are carried out for different population sizes to check the convergence of the GA.

6.12 Discussion

Selecting GA parameters like mutation rate, crossover rate, and population size, is a very difficult task due to the many possible variations and combinations in the algorithm operators and objective functions. In addition, the GA relies on random number generators for creating the population, crossover, and mutation. A different random number seed produces different results. Comparing all the different combinations of parameters settings and operators options and averaging the results to reduce random variations for a wide range of objective functions is an intimidating task. After all, another dimension of complexity is the high sensitivity and dependency of parameter settings to the objective functions. Parameter setting that could achieve excellent performance with objective function A, could easily achieve poor results with objective function B. Consequently, different studies result in different conclusions about the optimum parameter values and type of GA operators.

Although there are obstacles that still need to be tackled in the way of the GA, our study in this chapter performs several sets of basic experiments to find general recommendations for the GA parameters and operators settings for dynamic and changing cost surface objective functions. Based on our experimental study, some general recommendations are given. First, the Tournament selection operator usually performs best and outperforms the other selection operator. It performs better with a large population in terms of GA convergence time because it does not need ordering for the different individuals. Small Tournament-size allows wider search space and worse convergence time, whilst high Tournament-size allows better convergence time and smaller search space. Second, the deterministic crossover operators such as arithmetic and heuristic operators outperform the random crossover operators such as single-point or two-point crossover because their expected behaviours help out in reducing the randomness nature of the GA. Third, the Matlab Gaussian mutation and adaptive feasible operators are usually a superior option over uniform mutation because they are based on variable mutation rate. Finally, several tests have to be carried out to check the best value for mutation rate, crossover rate, and population size for the problem under consideration. These parameters have high impacts on the GA performance. However they are tightly dependent on the objective functions. Usually the crossover operator is less than 0.8 and the mutation operator is less than 0.2. Extreme values for both parameters (i.e. 0 or 1) perform poor in most situations.

Chapter 7

The Performance Evaluation and Results Study

The performance evaluation and results study for our developed algorithm are conducted in this chapter. Practically, four developed algorithms are simulated, evaluated, and compared with three different reference algorithms that are developed and simulated using the same simulation environment and models. The first ANS algorithm has been developed for co-existed WWAN and WLAN in chapter 4. It is based on both FL and SMART MCDM. The second algorithm is a GA-optimized version for the first algorithm. The third ANS algorithm has been developed for co-existed WWAN, WLAN, and WMAN in chapter 5. It is based on both FL and AHP MCDM. The forth algorithm is a GA-optimized version for the third algorithm.

This chapter is organized into six sections. The following points present the outlines of the sections in this chapters.

Section 7.1: presents the most common evolution mechanisms for the ANS algorithms and justifies our usage for the simulation based evolution approach.

Section 7.2: builds out the system, mobility, propagation, service, and traffic models that are used to simulate our algorithms.

Section 7.3: presents the used performance metrics and the reference algorithms.

Section 7.4: presents the simulation results of our FL-SMART and FL-SMART-GA algorithms and compares them with the results of the reference algorithms. The section consists of four subsections. Each subsection shows the achieved results with respect to one performance metric.

Section 7.5: presents the simulation results of our FL-AHP and FL-AHP-GA algo-

rithms and compares them with the results of the reference algorithms. The section consists of four subsections. Each subsection shows the achieved results with respect to one performance metric.
Section 7.6: discuss and analyzes the achieved result in sections 7.4 and 7.5. -

7.1 The Evaluation Mechanisms

The most common evolution mechanisms for the ANS algorithms and the other CRRM and RRM solutions include the analytical approach, the field trials approach and the simulation approach. This section justifies the usage of the simulation approach for performance evolution of our algorithms.

The analytical approach is based on simple mathematical models. This approach can quickly give a preliminary idea about the performance of some ANS algorithms for simplified ANS scenarios. This type of study has the advantages of having a lower cost and requiring less effort than other methods. However, more detailed studies for complex systems such as heterogeneous systems with heterogeneous traffic are problematic due to the high complexity and uncertainties involved in these systems. This approach is valid only under specified constraints such as the assumptions of a very low number of users and a very small number of RATs and cells. Actual ANS procedures are quite complicated and real world situations and scenarios make this approach complex and mathematically intractable. As a result, the use of the analytical approach is often limited to obtaining general trends for the performance of the RRM mechanisms.

The field trials approach is to carry out field tests in a trial or operational network. For a specific network configuration, this method can provide the most accurate evaluation for the system performance. However, this option requires the availability of the network itself, which is much more difficult in our case where more than one network have to be possible. Moreover, the results achieved by this approach tend to be network specific, depend on the network configuration and environment and differ from network to network.

The computer aided simulations of the system under study is another performance evaluation approach. The processing power of current computers allows the inclusion of complex models and algorithms in the system evaluation with reasonable cost and time. The simulation approach allows incorporation of many features of the required system into the evaluation framework and obtaining more precise results provided that the simulation models adequately capture the real system behaviour. As a result, computer based simulations are the most widely used and preferred solution for the evaluation and validation of the different RRM mechanisms including the ANS algorithms. This approach provides a common, easy, fast, cost-effective test-bed for the comparison of different ANS algorithms and a clear insight into the behaviour of the system with reasonable accuracy.

Before going further in building our simulation models, some of the simulation approaches that have been used for evaluating the ANS solutions in the literature so far are briefly touched here.

[132] addresses the impact of multi-mode terminals in an EDGE/UMTS heterogeneous network with multi-service provisioning. A simulation scenario with UTRAN and GERAN access technologies is used. A 2.25x2.25 km^2 area with 7 collocated omni-directional cells for GERAN and UTRAN is considered. For the propagation model, the urban macrocells model is assumed with a shadowing deviation of 10 dB. Mix of voice and data services with users moving at 3 km/hr are considered.

In [133] a mechanism to perform JRRM that is based on fuzzy-Neural methodology is introduced. A multi-cellular and multi-RAT scenario including 4 UMTS cells, 2 GERAN cells and one WLAN access point is considered. Each cell is characterized by a circular coverage area. The cell radius for UMTS is 650 meters, for GERAN it is 1 km and for WLAN it is 150 meters. A mobility model with users moving according to a random walk model is adopted, with a randomly assigned speed between 0 and 50 km/hr. Two different propagation models are used, one for both UMTS and GERAN and the other for WLAN. Both models are Hata based models and consider a shadowing model with 7 dB standard deviation. The services model considers three types of services: conversational, streaming and interactive.

An algorithm to solve the problem of selecting the optimum network for multicast services in the overlapping coverage of mobile and broadcasting networks is proposed in [134]. The proposed algorithm is evaluated by means of simulations using Matlab. The overlapping networks consist of 3GPP Multimedia Broadcast and Multicast Services (MBMS) with seven cells and Digital Video Broadcasting-Handheld (DVB-H) with one cell. Four types of service with different QoS requirements are assumed. In [135] an RAT selection algorithm based on the fittingness factor concept, which is a generic representation of the different factors that may influence the RAT selection decision is proposed. The same simulation environment and models proposed in [134] are used.

[136] proposes a joint admission control and scheduling scheme based on fairness, available bandwidth and user mobility characteristics in the context of co-existed CDMA-2000 and IEEE 802.11 wireless technologies. A Matlab based simulation environment that comprises one CDMA-2000 macrocell and one IEEE 802.11 microcell is used. Each cell has a square shape, where the length of macrocell and microcell are 2000 meters and 200 meters respectively. The number of users in the system is 100 users. The speed is assumed to be normally distributed with a mean speed of 0 km/hr and standard deviation 14.4 km/hr.

In fact, [139, 132, 133, 134, 135, 136] shows that there is not standard and common simulation models that could be used to evaluate the ANS solutions. It is believed that, the most impact on the ANS simulation results comes from the system and service models. However, the existed works use many different system and service models. To give our results more creditability, we use more than one system and service models.

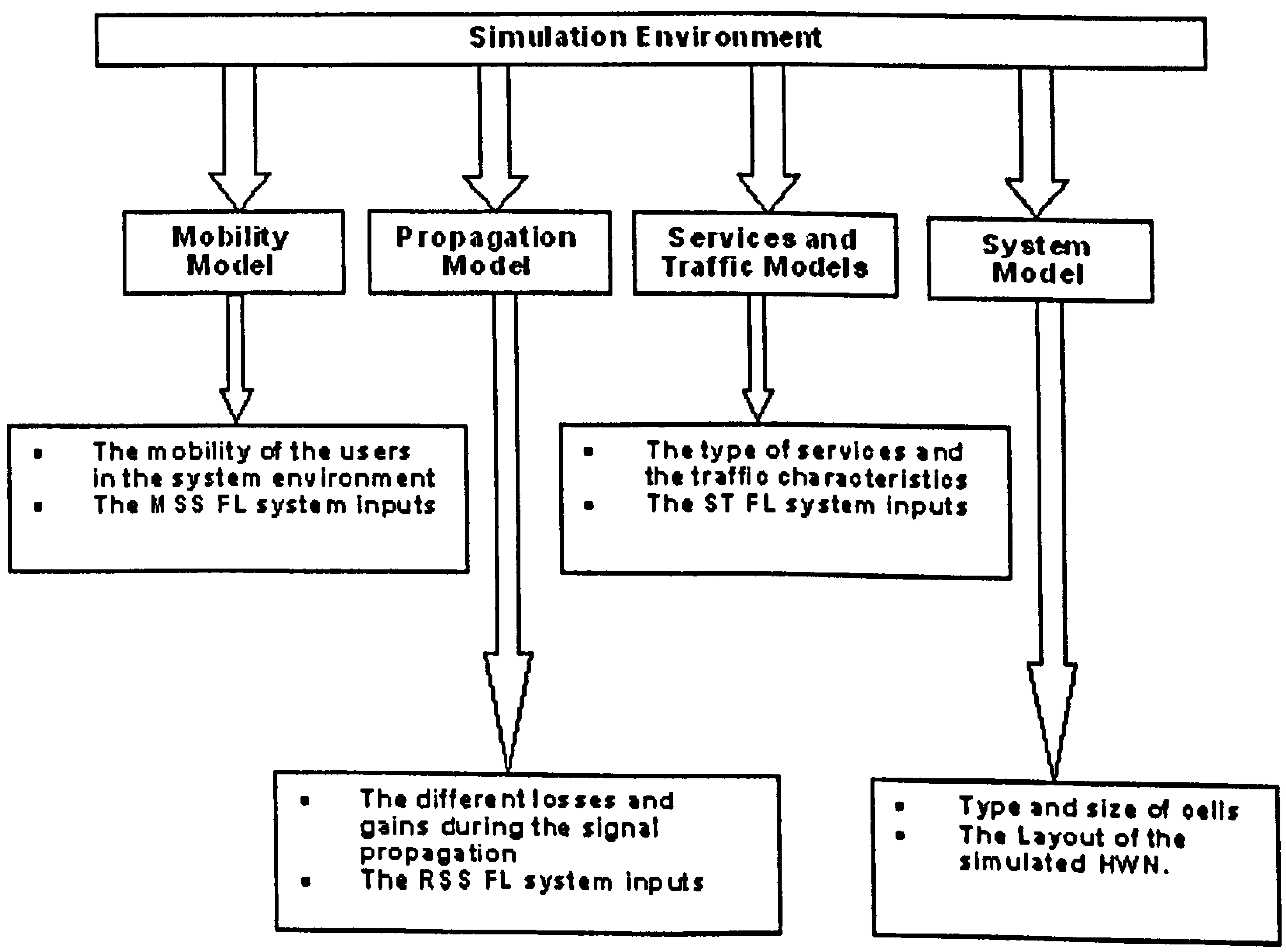

Figure 7.1: The simulation models

7.2 The Simulation Models

The FL and GA components have been implemented using the Matlab (R2006) [137] FL and GA toolboxes respectively. The MCDM components have been implemented using the Matlab programming language. Our developed algorithms are evaluated using the simulation approach. MATLAB-based toolbox called RUNE [17] has been used for creating the simulation models and environments. RUNE is originated by Ericsson research [138] and it is a special purpose simulator that makes it possible to simulate the RRM mechanisms in the cellular networks. RUNE is well verified and widely used simulator in the wireless communication field [139, 140, 141, 142, 143].

To create the simulation environment, we need to define several models including a system model, a mobility model, a propagation model, a traffic model, and services model. All the models are borrowed from the RUNE toolbox. Figure 7.1 summarizes the needed simulation models. The following subsections describe in detail the different simulation models.

7.2.1 The System Model

The system model specifies the type of networks and the number and characteristics of the cells. In our model, all the cells have standard hexagonal shapes with omni-directional antennas. Two different system models are used. The first one is used to simulate the ANS algorithm for co-existing WWAN and WLAN that is developed in chapter 4. The second one is used to simulate the ANS algorithm for co-existing WWAN, WMAN, and WLAN that is developed in chapter 5.

The first system model considers the coexistence of two types of wireless access networks. The first network is a CDMA based WWAN with seven macro cells with cell radius of 1000 meters and the second one is a TDMA based WLAN with eighty one micro cells with a cell radius of 250 meters. Figure 7.2 shows the first system model.

The second system model considers the coexistence of three types of wireless access networks. The first network is a CDMA based WWAN with seven macro cells with a cell radius of 750 meters. The second one is a TDMA based WLAN with eighty four micro cells with a cell radius of 100 meters. The third one is a CDMA based WMAN with twelve macro cells with a cell radius of 375 meters. Figure 7.3 shows the second system model.

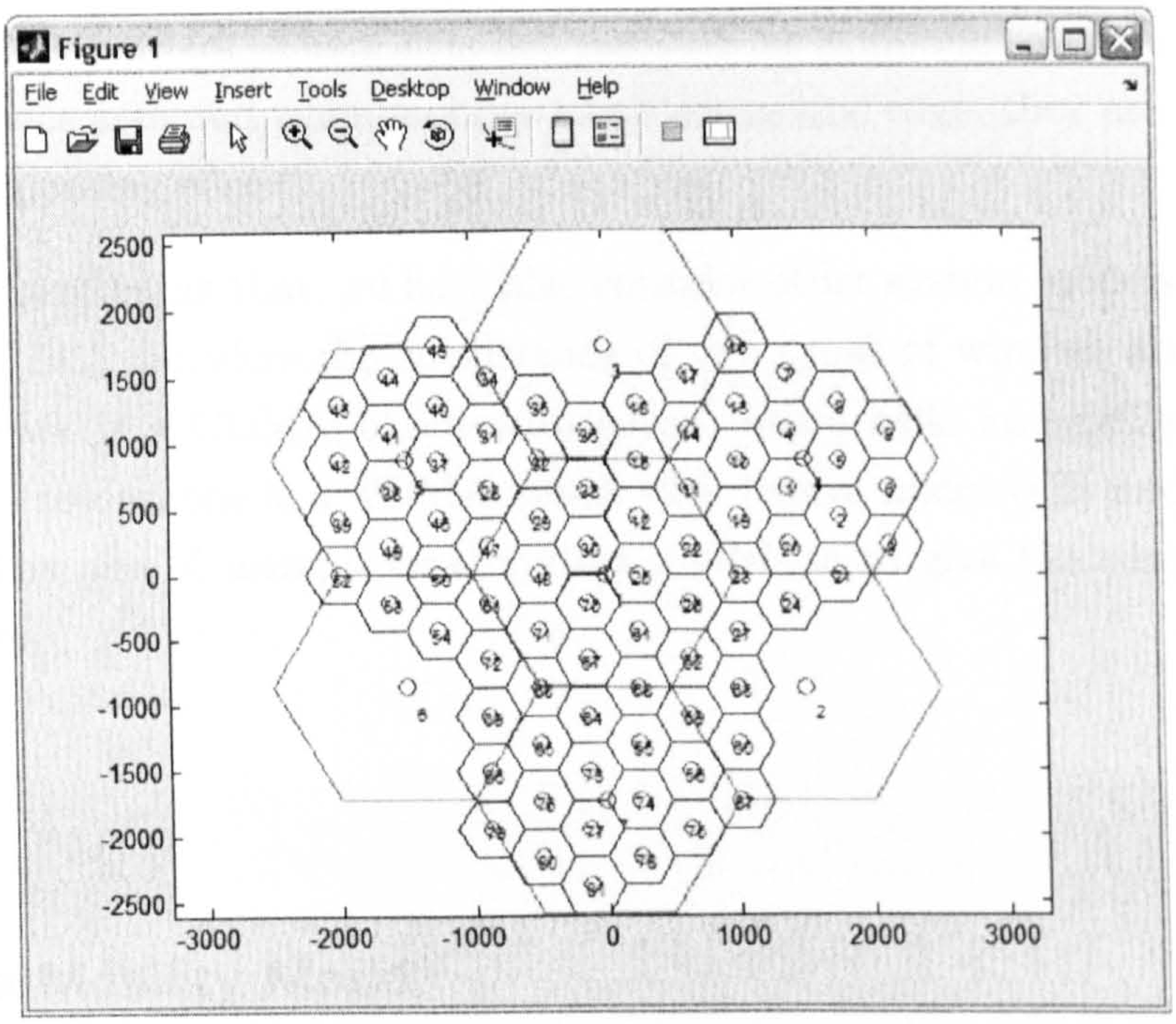

Figure 7.2: The first system model

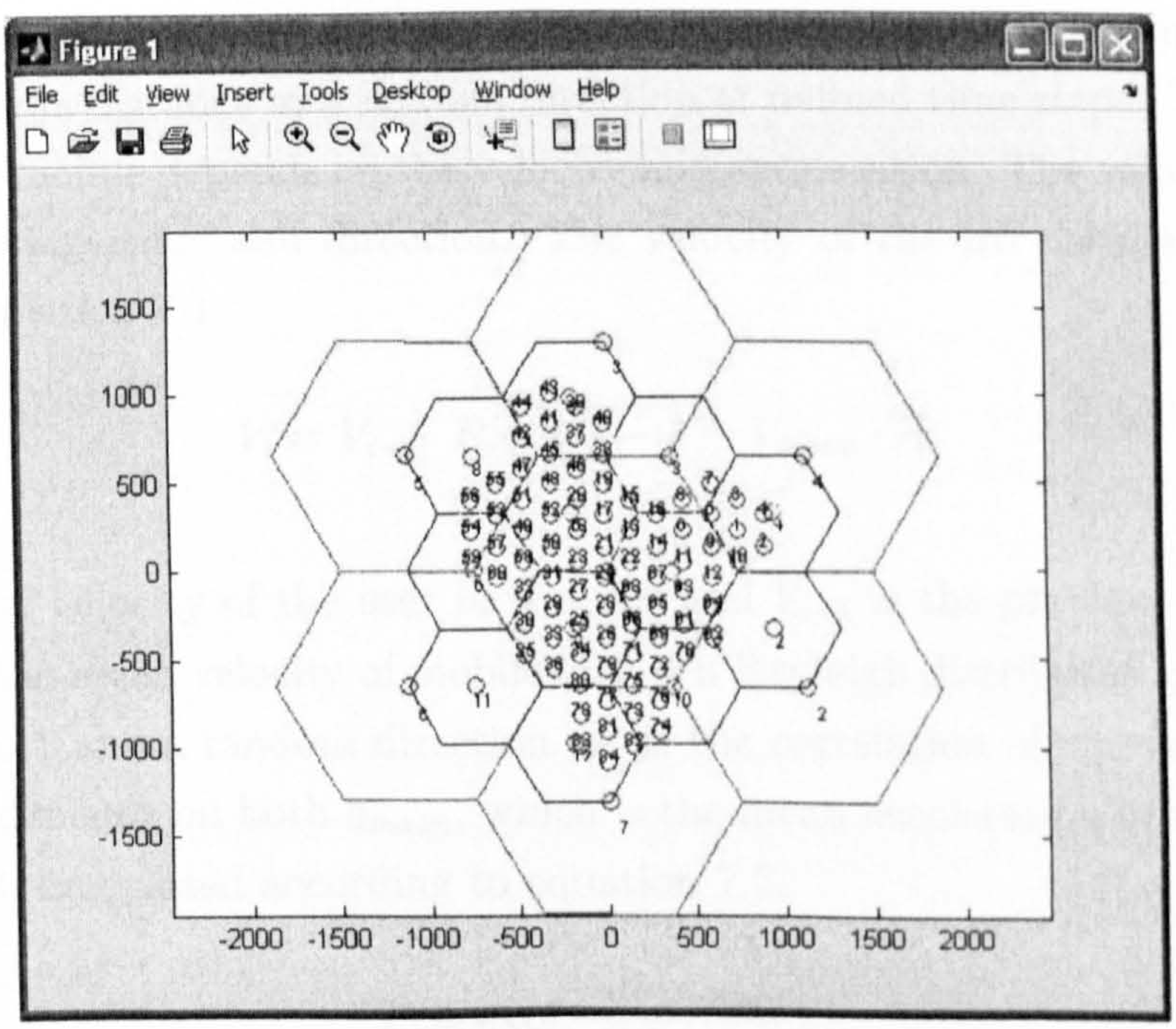

Figure 7.3: The second system model

To model a very large network and to avoid borders, the wrap around function of RUNE is used. This consists of wrapping the whole cells in a way that the service area does not have any borders. Then, it is not possible for a mobile to move over the edge outside the service area and when mobiles move across one edge, they are automatically moved to the opposing edge.

It is worth mentioning that, we have also consider other system models in our related works in [145]. [145] considers the coexistence of two types of wireless access networks. The first network is a CDMA based with seven macro cells and cell radius = 1000 meters and the second one is a TDMA based with twelve micro cells and cell radius = 500 meters. The aim of using several system models is to give the simulation results more credibility.

7.2.2 The Mobility Model

The mobility model simulates the mobility of the users in the system environment. In our mobility model, the mobiles are randomly distributed over the system. Each mobile is moved a random distance in a random direction at defined time steps. The movement pattern of each mobile depends on the velocity and acceleration. The velocity is a vector quantity with magnitude and direction. The velocity of the ith mobile V_i is updated according to equation 7.1.

$$V_i = V_{i-1} \cdot P + \sqrt{1 - P^2} \cdot V_{mean} \cdot X \tag{7.1}$$

V_i is the new velocity of the user in [km/hr] and V_{i-1} is the previous velocity of the user. V_{mean} is the mean velocity of mobiles. X is a Rayleigh distributed magnitude with mean equals to 1 and a random direction. P is the correlation of the velocity between time steps. P depends on both a_{mean}, which is the mean acceleration of the mobile user and V_{mean}. P is calculated according to equation 7.2.

$$P = \exp(\frac{-dt \cdot a_{mean}}{V_{mean}}) \tag{7.2}$$

V_{mean} has been set to 10 km/hr and a_{mean} has been set to 1 km/hr^2. Again, thanks to the wraparound, if a mobile moves across the left edge it is moved to the right edge. Figure 7.4 shows the users, in blue, over the wireless environment.

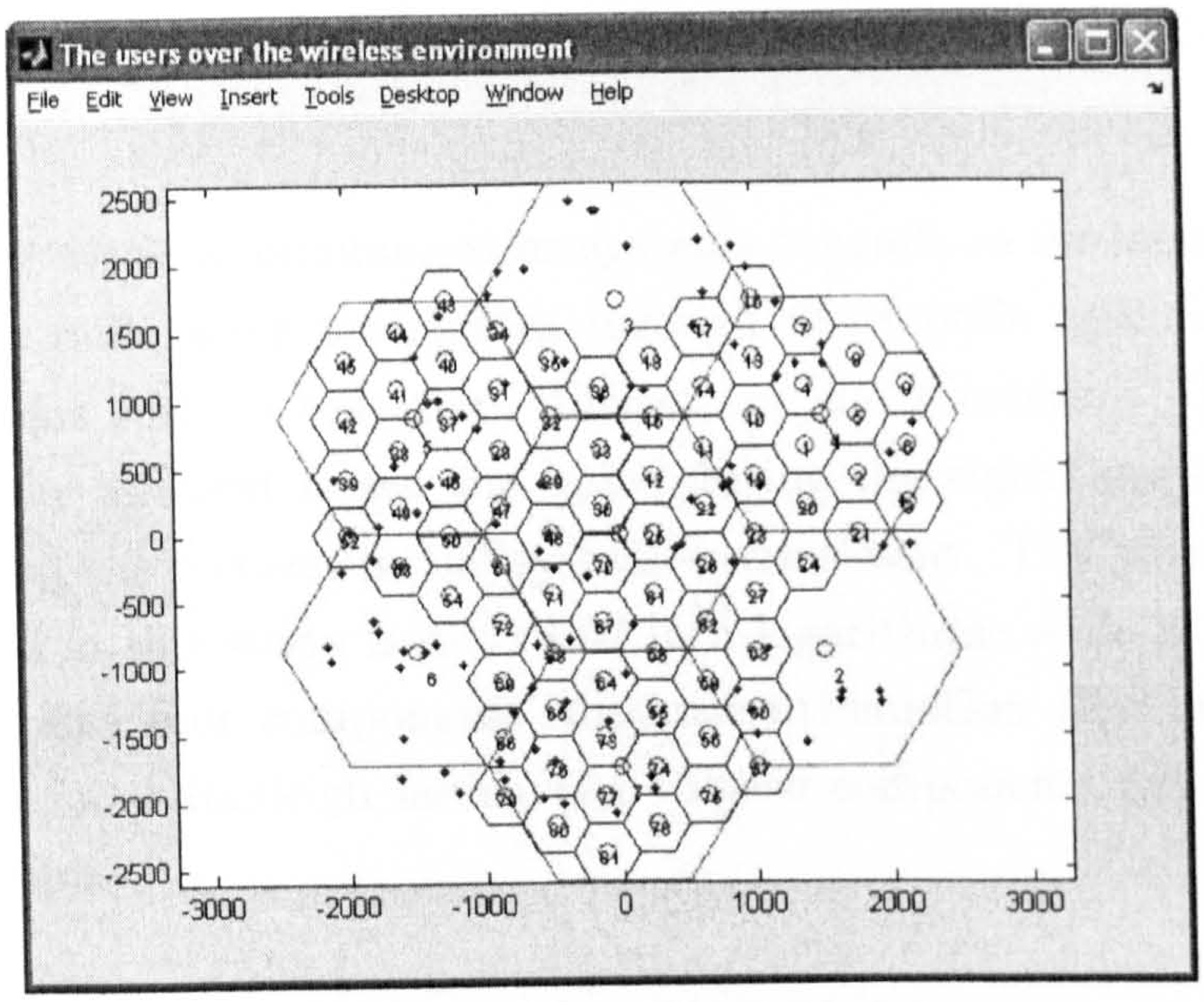

Figure 7.4: The users over the wireless environment

7.2.3 The Services Model

The services model specifies the type of services and their percentages of use in the system environment. Two different service models have been considered. In the first model, four types of services have been considered in our simulation. These services are mainly characterized by their Required Bit Rate (RBR) and one-way end-to-end Propagation Delay Requirements (PDR). The first service type needs low bit rate and low propagation delay such as speech and voice. The second service type needs medium bit rate and low propagation delays such as low bit rate real time video telephony. The third service type needs medium bit rate and medium propagation delay such as high bit rate streaming video. The forth service type needs high bit rate and it can accept high propagation delay such as non-real time data traffic. N mobiles are generated and randomly distributed among the four classes of services. Table 7.1 summarizes practical values for RBR and PDR characteristics of the considered services [146, 147].

In the second model, adaptive service model is considered in our simulation. In this model, the services are mainly characterized by their RBR and PDR. The service i is characterized by an integer number for RBR_i in the range of 12 kbps to 384 kbps and by an integer number for PDR_i in the range of 50 ms to 1000 ms.

7.2.4 The Propagation Models

The performance of wireless communication systems depends on the mobile radio channel significantly. The radio wave propagates through the mobile radio channel through different mechanisms such as reflection, diffraction, and scattering. The propagation model simulates the different losses and gains during the signal propagation between the transmitter and the receiver in the system environment. The wireless propagation model that is used in this study is described in a logarithmic scale as in equation 7.3. Equation 7.3 contains four components, distance attenuation G_D, antenna gain G_A, shadow fading G_F, and Rayleigh fading G_R. These components are described in the following paragraphs.

$$G = G_D + G_A + G_F + G_R \tag{7.3}$$

The Distance Attenuation G_D and the Antenna Gain G_A

The signal attenuates due the distance between the transmitter and the receiver. The attenuation G_D is given by the Okumura-Hata formula 7.4 [148]. In this formula, d is the distance to the transmitter. The parameter α is the distance attenuation coefficient. It determines how much the power decays as a function of distance from the base station. β is a constant used to model the effect of carrier frequency, the antenna size and other physical parameters. It is interpreted as the free space path gain at a distance of one meter from the transmitter antenna. Figure 7.5 shows an example when only the distance dependent component is modelled, whilst the other components of the propagation models are set to zero. In this example, α has been set to 4 and β has been set to -28 dB. The G_A component adds the antenna gain in dB given the mobiles angle

Table 7.1: The services RBR and PDR characteristics in the first service model

Service Type	RBR value (kbps)	PDR value (ms)	Service type example
First Type	12.2	200	speech and voice
Second Type	64	600	real time video telephony
Third Type	144	400	streaming video
Forth Type	384	1400	non-real time data traffic

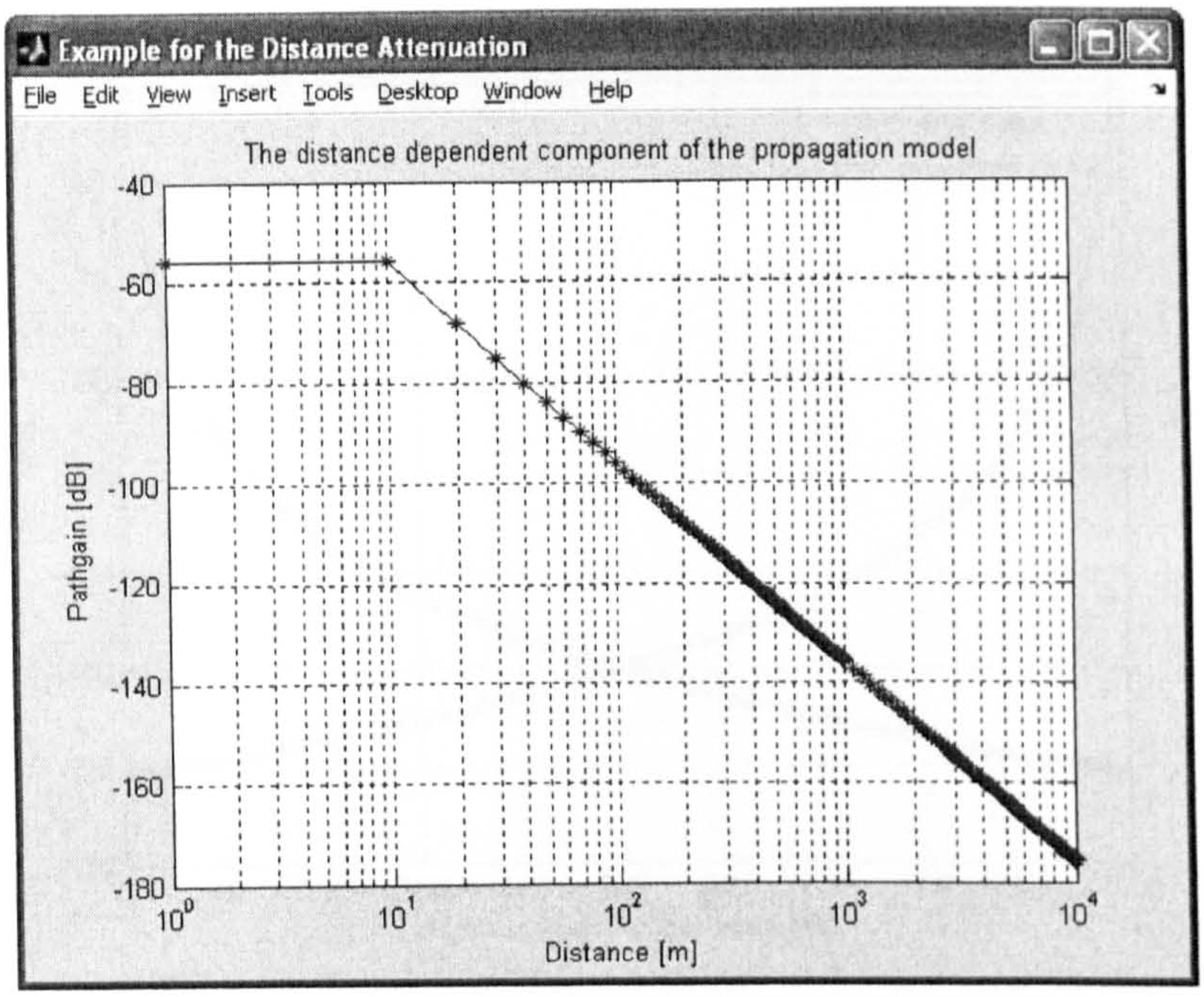

Figure 7.5: The distance dependent component

relative to the base station's forward direction.

$$[t]G_D = -\{\beta + 10 \cdot \alpha \cdot \log(d)\} \tag{7.4}$$

The Shadow Fading G_F

The signals are more attenuated when a large object, such as a hill or a building, is located between the transmitter and the receiver, than in the case where the two units are in line of sight. This effect is statistically modelled by the shadow fading component. The lognormal distribution with 0 dB mean and standard deviation σ is typically used for this purpose. Figure 7.6 shows the profile of the RSS from two bases that are located 1000 meters away from each other as the mobile station moves along the line joining the bases in case no shadow fading is considered (i.e. only distance fading and antenna gain are considered) and both bases have omni directional antennas. RSS decreases monotonically as the mobile station moves away from the bases. α has been set to 3.5 and β has been set to -28 dB.

Figure 7.7 shows the RSS profile from the two bases in case of shadow fading with *corrdist* has been set to 110 meters and σ has been set to 6 dB is considered. The

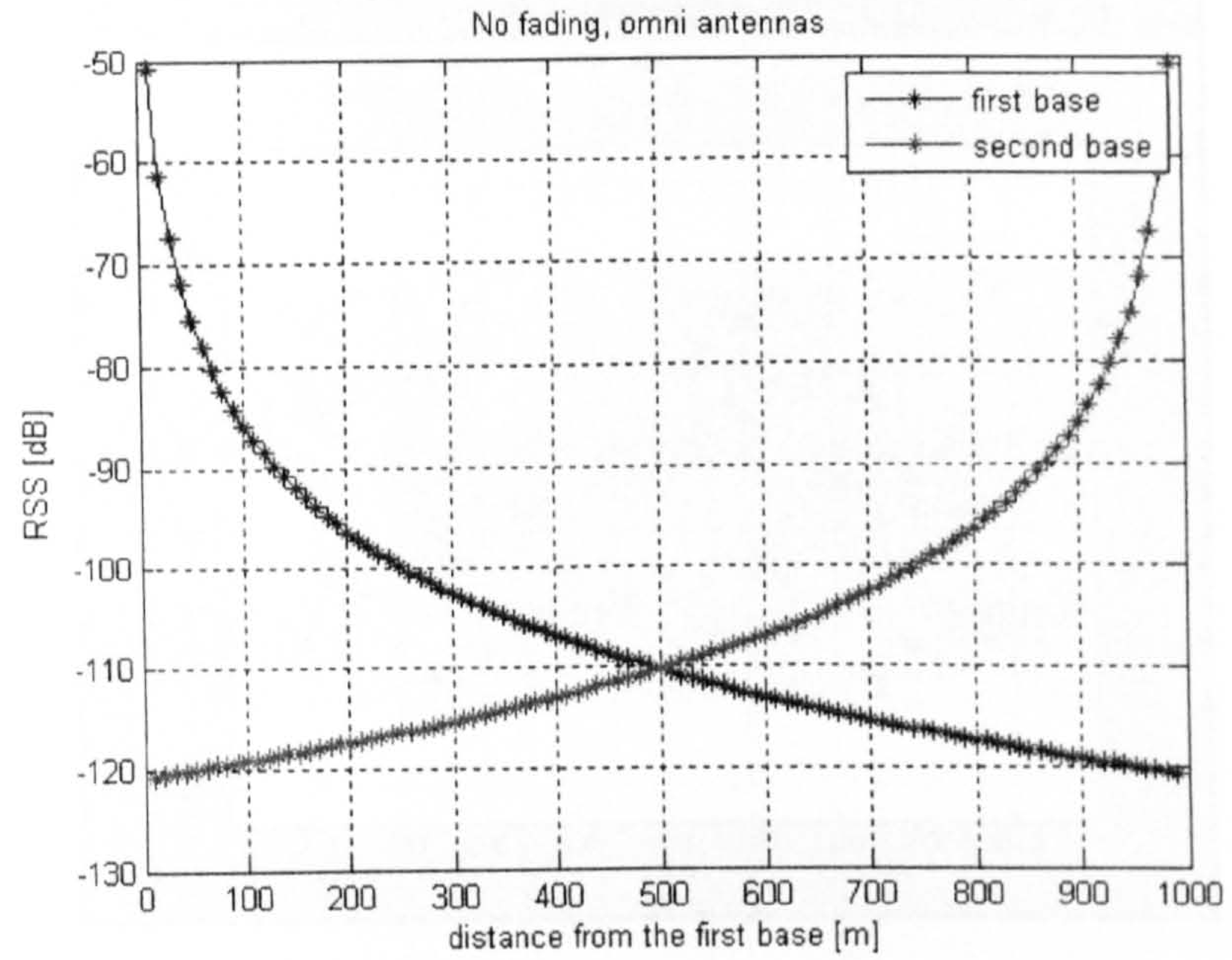

Figure 7.6: Typical profile of RSS from two bases when no shadow fading is considered

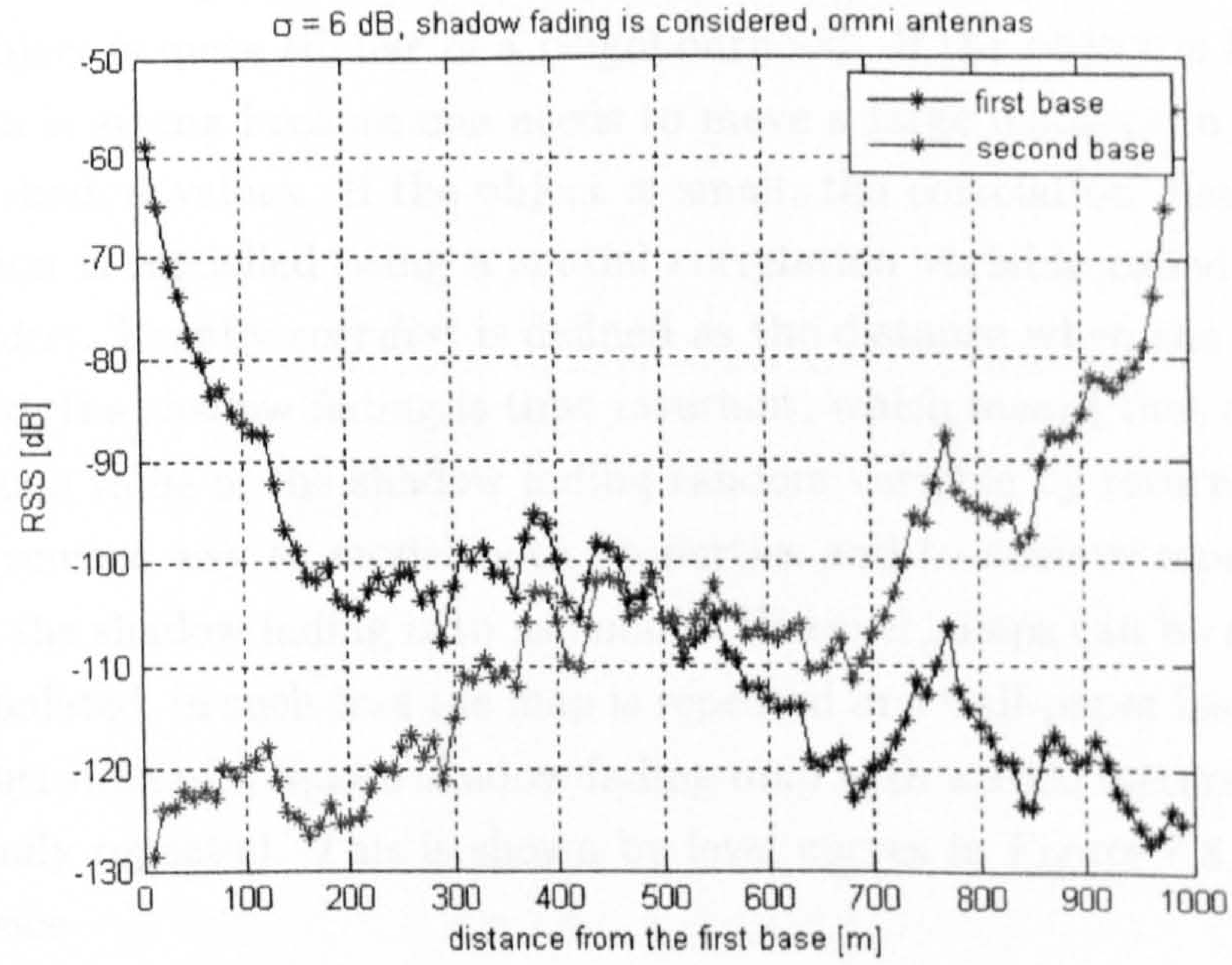

Figure 7.7: RSS from two bases when shadow fading is considered

zig-zag line includes the shadow fading component effects.

Shadow fading has two important properties. First, it is space correlated where the

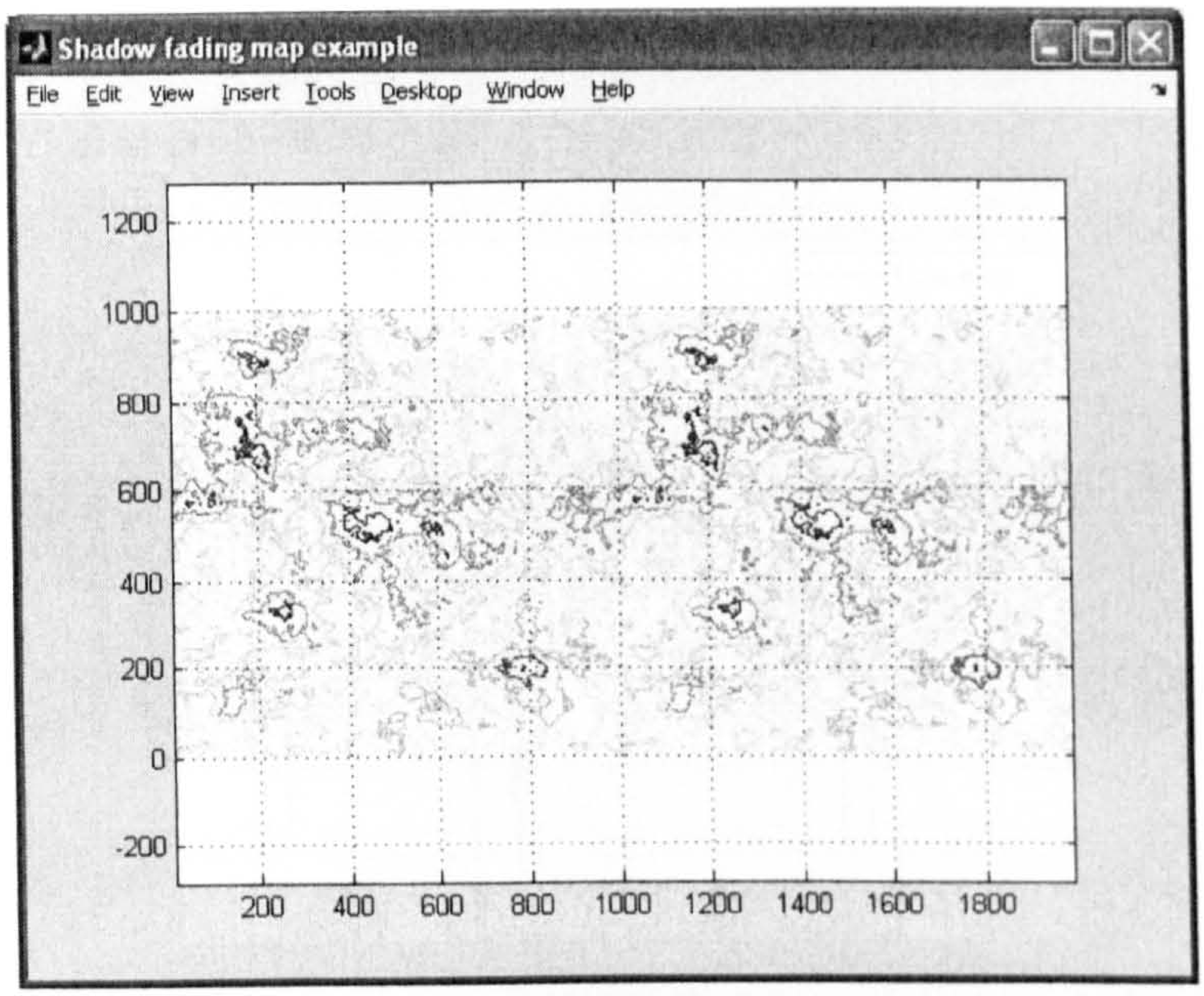

Figure 7.8: Example of shadow fading maps

shadow effects for a large object cover a larger area and therefore, the extra attenuation due to this object is quite similar in a neighbourhood. If the object is large (e.g. hill), the correlation is strong because one needs to move a large distance in order to obtain uncorrelated shadow values. If the object is small, the correlation distance is smaller. This correlation is modelled using a spatial correlation variable called the correlation distance *corrdist*. Usually *corrdist* is defined as the distance when the correlation falls to e^{-1}. Second, the shadow fading is time invariant, which means that one would experiences the same value of the shadow fading random variable by returning to the same place. A convenient way to model both properties and to achieve repeatability in the generation of the shadow fading is to use maps. However, maps can be smaller than the area to be simulated, in such case the map is repeated in a wall-paper fashion. Figure 7.8 shows the generation of a square shadow fading map with a 1000 meters edge. The map can be cyclically repeated. This is shown by level curves in Figure 7.8, where the map is repeated once.

The Rayleigh Fading G_R

This component considers the effect of the signal multi-path propagation with no line of sight or dominant path between the transmitter and receiver and it is a Rayleigh distributed. The nature of this type of fading causes the changes to occur very quickly,

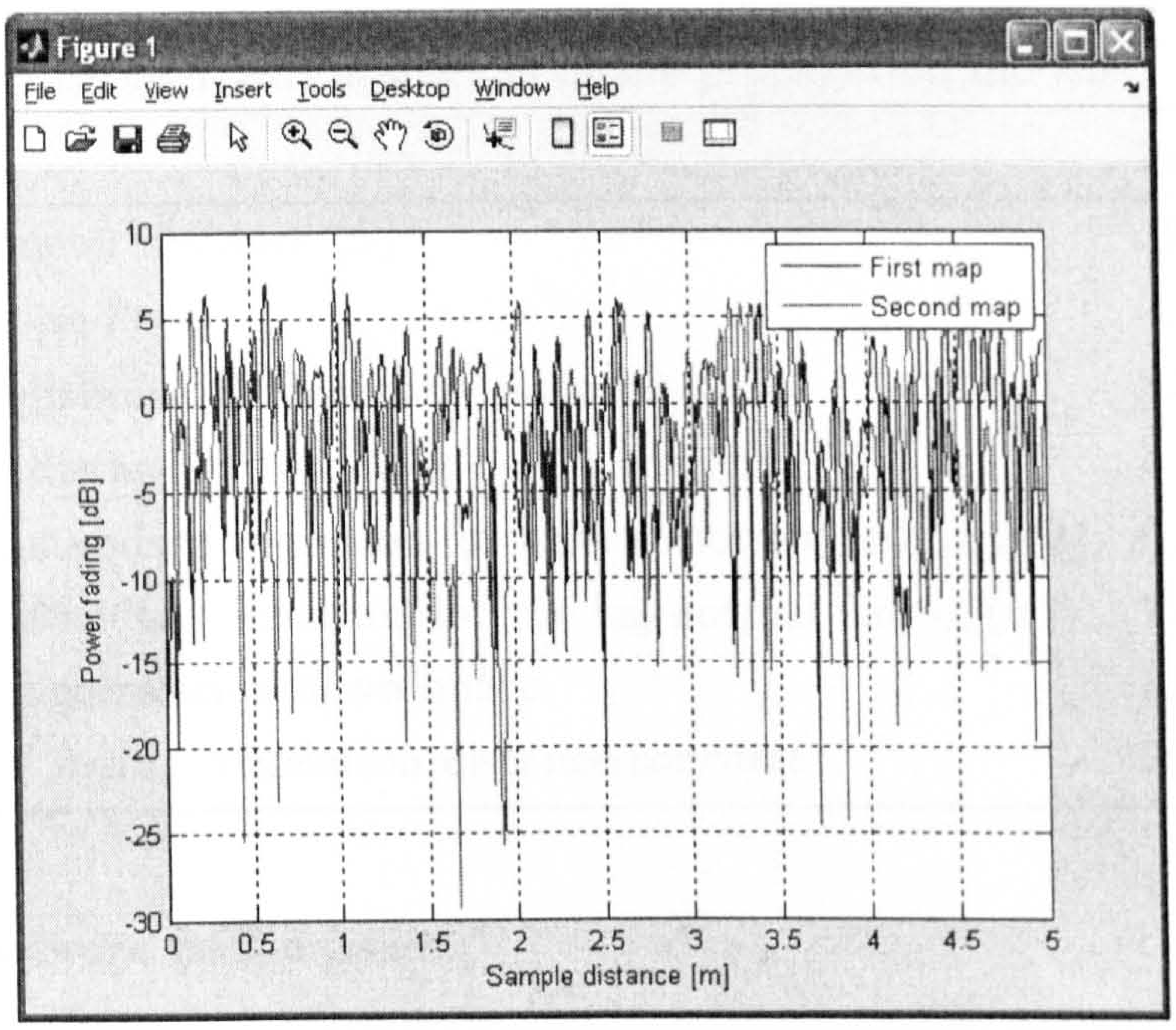

Figure 7.9: Two Rayleigh maps

and sometimes this type of fading is called fast fading. To model this component, a Rayleigh fading map is created with complex samples. This map is generated by filtering white noise through a Bessel function. To make the map periodic, a Fourier method is used, so the designated area is covered with a Rayleigh pattern much like a wall paper. Then, based on the position of the user, a Rayleigh value is used from the map created. Figure 7.9 creates two Rayleigh fading maps spanning a square area of 1000 m for a carrier frequency equals to $f_c = 1950$ MHz. Table 7.2 shows the main parameters of the developed propagation models.

7.2.5 The Traffic Model

The users of all four services are generated according to the Poisson process [149, 150]. This means that the time between subsequent arrivals of new calls (births) is exponentially distributed, as are the times between subsequent departures (death). The service holding time is exponential distribution with a mean holding time equal to 50 seconds. No specific traffic models for packet based services are considered (i.e. the services are assumed to be like circuit-switched services). This assumption does not affect the results of the initial ANS algorithms, because the initial ANS does not consider the resource

Table 7.2: Parameters of the propagation models

Parameter	Value
Gain at 1 meter distance (β)	-28 dB
Thermal noise floor	-118 (dBm)
Microcells distance attenuation coefficient ($\alpha 1$)	3.3
Macrocells distance attenuation coefficient ($\alpha 2$)	4
Macrocells standard deviation for the log-normal fading ($\sigma 2$)	6 dB
Microcells standard deviation for the log-normal fading ($\sigma 1$)	7 dB
Log-normal correlation down link ρ	0.5
Log-normal fading correlation distance $corrdist$	20 m

allocation and network traffics issues.

7.3 The Performance Evaluation Metrics

The popular performance metrics for radio resource management algorithms include the network (call) level parameters, link (packet) level parameters and physical (bit) level parameters. The main network level parameters are call blocking probability, call dropping probability, and handoff dropping probability. The most important link level parameters are the packet error, loss rate and the packet delay. On the physical layer level, bit error rate is the most important metric. It can be noticed that all the above parameters have to be minimized to achieve better QoS and resources utilization. It is clearly noticeable that all these metrics are dependent on the local admission control and horizontal vertical handover algorithms in the loose coupled NGWN environment and they are also dependent on the JAC and VHO algorithms on the tight coupled NGWN environments.

It is worth mentioning that many ANS soultions do not distinguish between the initial ANS that happens due a new service request and the vertical handover ANS that happens due to different reasons such as severe signal degradation, bad link quality or to achieve load balancing. Furthermore, other works do not distinguish between the initial ANS and JAC. JAC usually goes one further step and allocates the resources for the user in the selected network. As a result, the used performance evaluation metrics in the previous work are more suitable for VHO and JAC rather than the initial ANS. In our study a new set of metrics are used to address solely the initial ANS performance independent from the other RRM and CRRM mechanisms.

Three performance evaluation metrics have been used to evaluate the performance of our algorithms. The used metrics are described briefly as follows:

- The percentage of users who are assigned to networks with better QoS conditions. This metric reflects the QoS point of view about the performance of the selection process. For simplicity, we can use the percentage of the users who are assigned to networks with stronger received signal (P_q).
- The percentage of users who are assigned to networks of their preference (P_u). This metric reflects the user point of view about the performance of the selection process.
- The usage percentage of the low-cost network resources (P_o). This metric reflects the operator point of view because it saves the resources of the high cost networks. P_o can be calculated as the percentage between the number of users in WLAN and the total number of users.

Three different reference algorithms are used to compare with our developed algorithms. The first algorithm is a service-type based selection algorithm where the services with low bit rate and high propagation delay requirements are directed into the WWAN, the services with high bit rate and low propagation delay requirements are directed into the WLAN, and the services with medium bit rate and medium propagation delay requirements are directed into the WMAN. The second algorithm is a terminal-speed based selection algorithm where high speed users are sent to the high-coverage network and the low and medium speed users are sent to the smaller coverage area networks. The third algorithm is a random-based selection algorithm where the users are assigned randomly to the co-existed networks.

7.4 The Performance Evaluation of the Combined FL and SMART based Algorithms

Some simulation results for the developed algorithms in chapter 4 are presented and analyzed in this section. The achieved values of P_q, P_u, and P_o by our algorithms are compared with the values achieved by the reference algorithms.

7.4.1 Percentage of Users with Better QoS (P_q)

From both Figure 7.10 and the numerical samples for P_q values shown in Table 7.3, the improvement in the percentage of the users who are assigned to networks with stronger received signal can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks with stronger received signal is 48.7%, 48.2%, and 50% in the service-type based selection, the terminal-speed based selection, and the random- based selection respectively. The same percentage with the combined FL and SMART solution is around 51.7% and around 61.9% in the GA-optimized version. In average, our developed FL-SMART solution achieves around 3% enhancement over the different reference algorithms. The optimized FL-SMART solution achieves around 13% enhancement over the different reference algorithms and around 10% over the non-optimized FL-SMART solution.

The criteria weights achieved by ObjFun1 (see chapter 6) are used for the GA-optimized solution. Figure 7.11 shows the weights assigned by GA for the SMART tool first objective function. The figure shows that the GA achieves best fitness function value equals to zero. GA gives the weight W_s high value while it keeps the rest of weights with much lower values. For the non-optimized version, all criteria weights have been set to 0.25, which means that all criteria have equal importance.

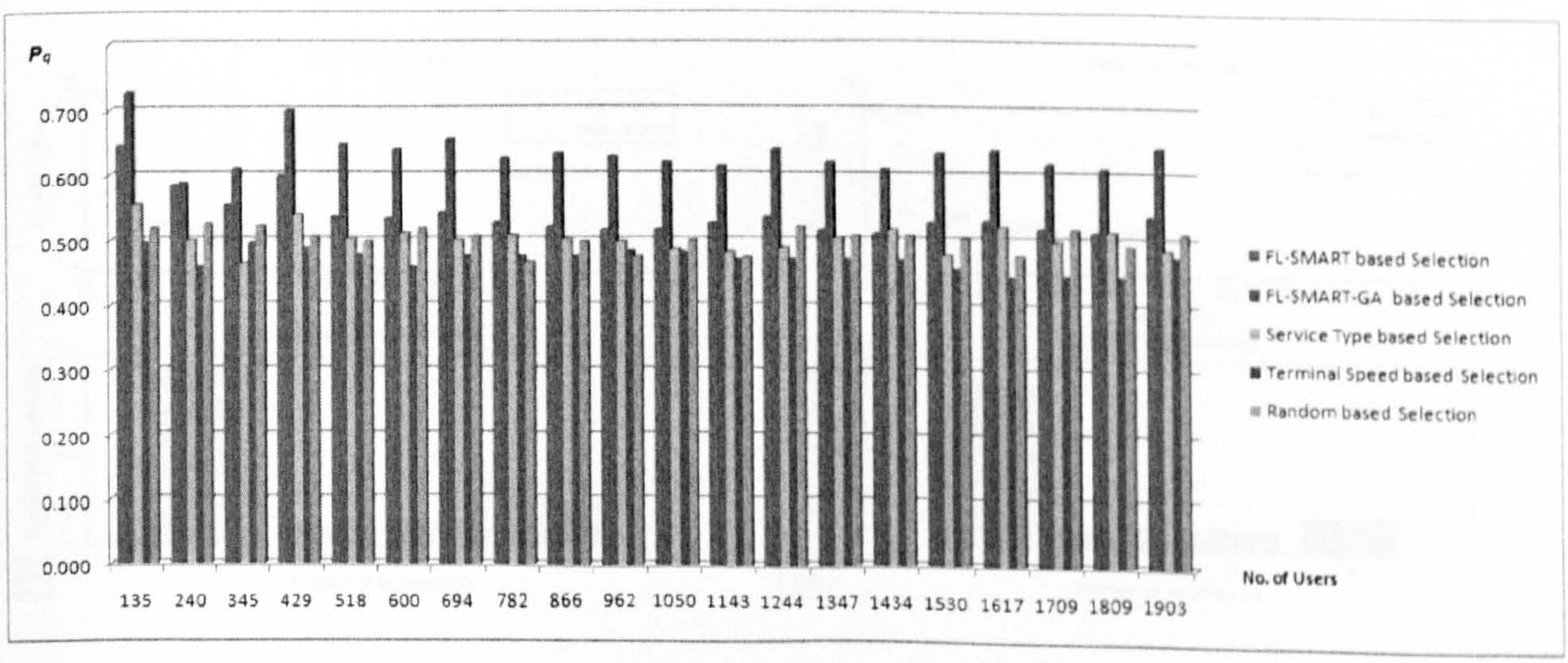

Figure 7.10: P_q values of the combined FL and SMART based algorithms against the reference algorithms

Table 7.3: P_q values of the combined FL and SMART based algorithms against the reference algorithms

No. of Users	FL-SMART selection P_q	FL-SMART-GA selection P_q	Service type selection P_q	Terminal-speed selection P_q	Random selection P_q
135	0.644	0.726	0.556	0.496	0.519
345	0.554	0.609	0.464	0.496	0.522
429	0.599	0.699	0.538	0.487	0.506
518	0.535	0.646	0.504	0.477	0.498
600	0.533	0.638	0.512	0.458	0.518
782	0.527	0.624	0.508	0.476	0.467
866	0.521	0.632	0.501	0.476	0.498
1050	0.517	0.619	0.487	0.482	0.500
1143	0.527	0.614	0.483	0.471	0.474
1244	0.535	0.639	0.489	0.472	0.521
1347	0.516	0.620	0.504	0.472	0.508
1434	0.511	0.609	0.517	0.470	0.508
1617	0.530	0.637	0.522	0.444	0.478
1709	0.513	0.617	0.499	0.446	0.518
1809	0.512	0.610	0.514	0.444	0.492
1903	0.539	0.642	0.488	0.476	0.513

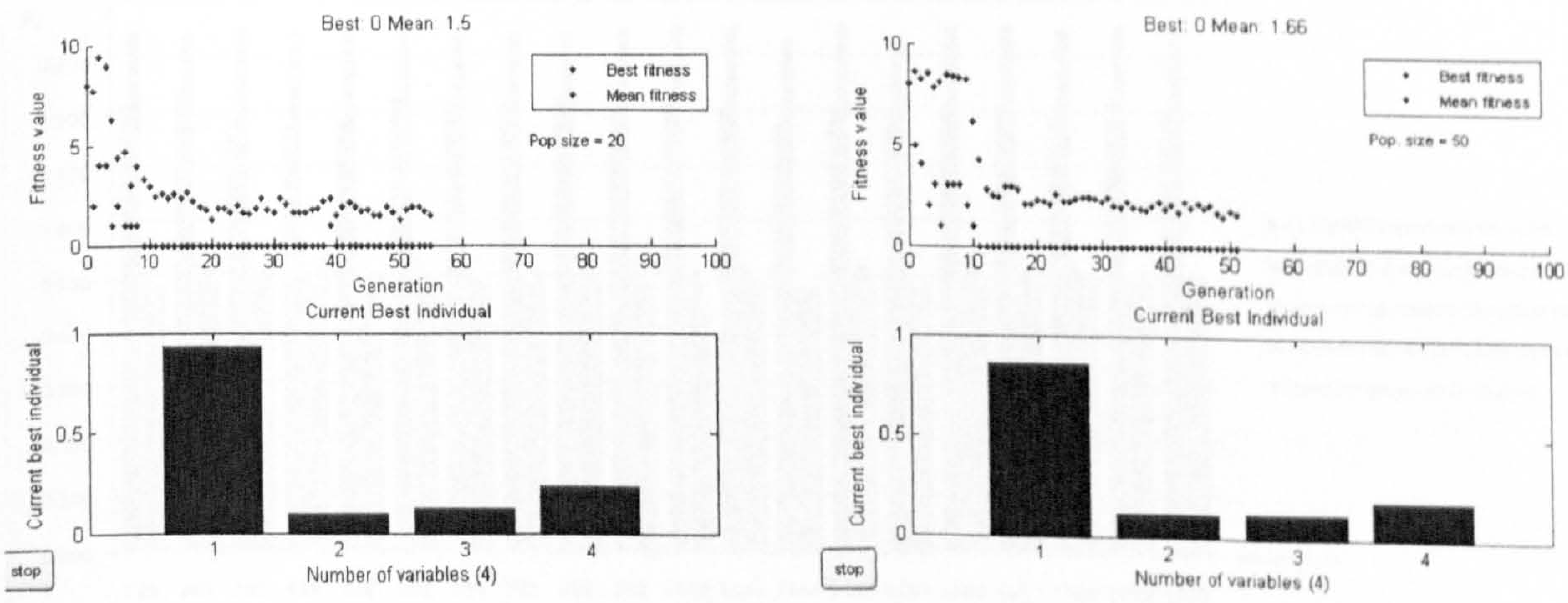

Figure 7.11: The weights assigned by GA for ObjFun1

7.4.2 Percentage of Satisfied Users (P_u)

From both Figure 7.12 and the numerical samples for P_u values shown in Table 7.4, the great improvement in the number of the satisfied users in our solutions can be seen. For example, with 1050 users in the environment, the percentage of satisfied users is 50.1%, 51.1%, and 45% in the service type based selection, the terminal-speed based selection, and the random-based selection respectively. The same percentage with the combined FL and SMATRT solution is around 82.5% and it is around 96% in the GA-optimized version. In average, our developed FL-SMART solution achieves around 31% enhancement over the different reference algorithms in terms of numbersof satisfied users. The optimized FL-SMART solution achieves around 54% enhancement over the different reference algorithms and around 14% enhancement over the non-optimized FL-SMART solution.

The criteria weights achieved by ObjFun2 are used for the GA-optimized solution. Figure 7.13 shows the weights assigned by GA for the SMART tool second objective function. The figure shows that the GA achieves best fitness value equals to zero. GA gives the weight W_u higher values while keep the rest of weights with much lower values.

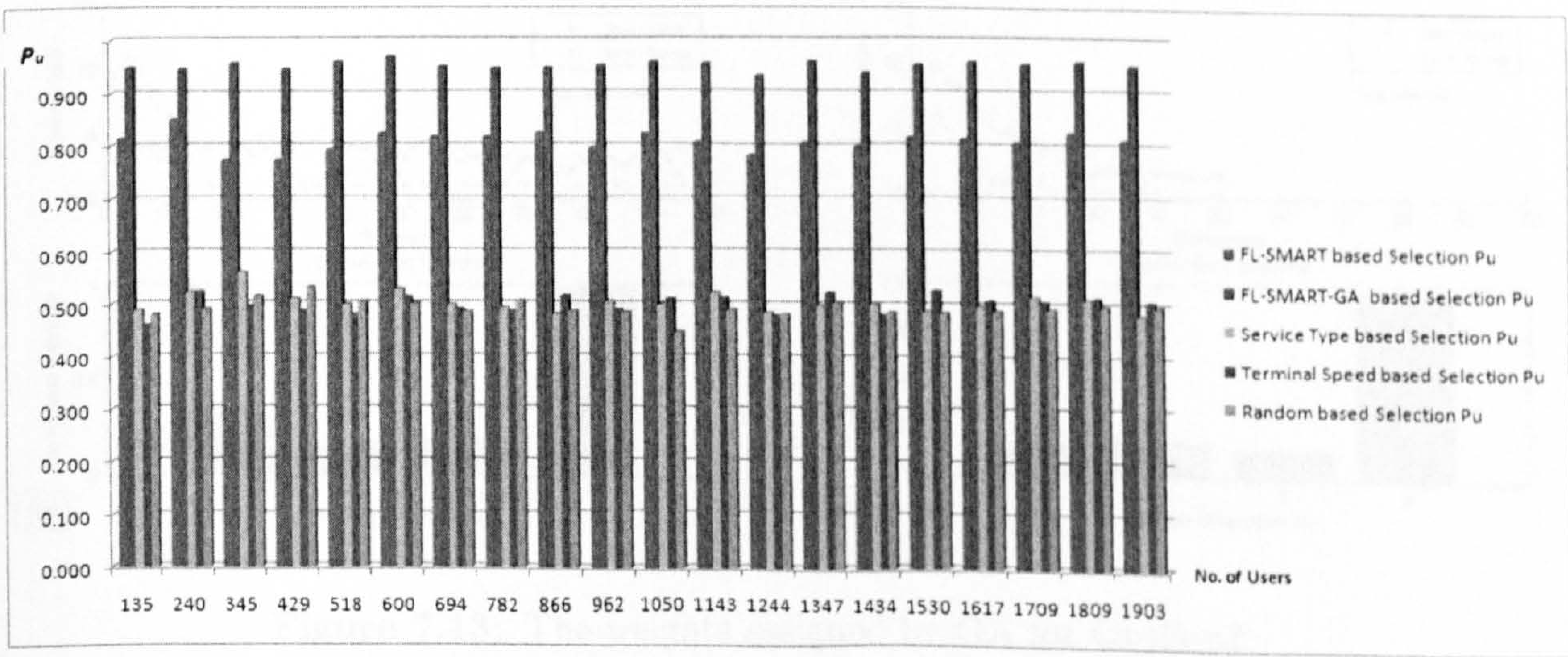

Figure 7.12: P_u values of the combined FL and SMART based algorithms against the reference algorithms

Table 7.4: P_u values of the combined FL and SMART based algorithms against the reference algorithms

No. of Users	FL-SMART selection P_u	FL-SMART-GA selection P_u	Service type selection P_u	Terminal-speed selection P_u	Random selection P_u
135	0.815	0.948	0.489	0.459	0.481
345	0.774	0.957	0.562	0.496	0.516
429	0.774	0.946	0.510	0.487	0.534
518	0.793	0.959	0.500	0.481	0.506
600	0.825	0.970	0.530	0.513	0.503
782	0.817	0.948	0.494	0.487	0.506
866	0.826	0.948	0.483	0.517	0.488
1050	0.825	0.960	0.501	0.511	0.450
1143	0.808	0.957	0.523	0.513	0.492
1244	0.784	0.936	0.486	0.481	0.483
1347	0.808	0.961	0.499	0.523	0.506
1434	0.799	0.940	0.503	0.482	0.487
1617	0.813	0.962	0.500	0.510	0.492
1709	0.807	0.957	0.518	0.508	0.494
1809	0.826	0.960	0.512	0.515	0.500
1903	0.811	0.954	0.484	0.509	0.500

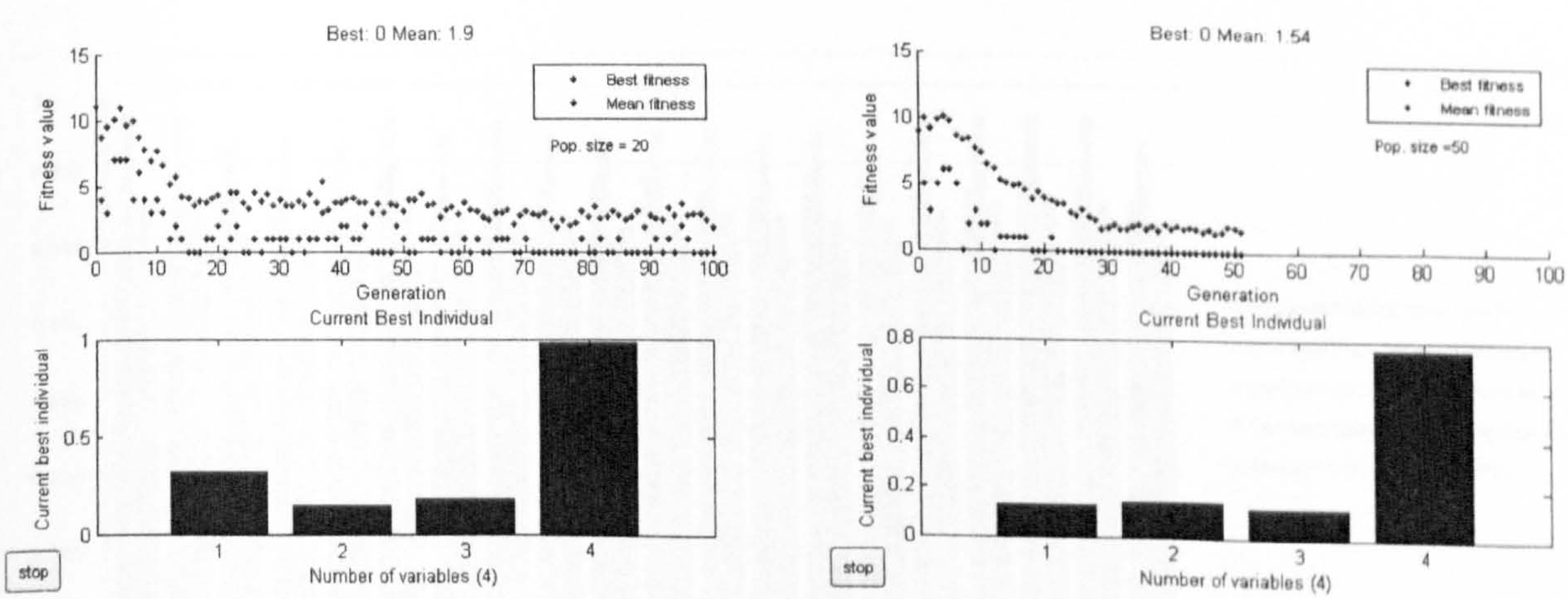

Figure 7.13: The weights assigned by GA for ObjFun2

7.4.3 Percentage of Users Assigned to Low-Cost Network (P_o)

From both Figure 7.14 and the numerical samples for P_o values shown in Table 7.5, the improvement in the percentage of the users who are assigned to low-cost network (i.e. WLAN) can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to the low-cost network is 51.3%, 53.5%, and 50.2% in the service type based selection, the terminal-speed based selection, and the random-based selection. The same percentage with the combined FL and SMART tool is around 58.1% and it is around 65% in our GA-optimized solution. In average, FL-SMART solution achieves around 7% enhancement over the service type based selection and random-based selection. It also achieves around 4% enhancement over the terminal-speed based selection. The optimized solution achieves around 14% enhancement over the service type based and random-based selection algorithms and around 11% over the terminal-speed based selection algorithm. It also achieves around 7% enhancement over the non-optimized FL-SMART solution.

The criteria weights achieved by ObjFun3 are used for the GA-optimized solution. Figure 7.15 shows the weights assigned by GA for the SMART tool third objective function. The figure shows that the GA achieves best fitness value approximately equals to zero. It shows that the GA converges and gives low values for W_s and W_u and higher values for W_v and W_t.

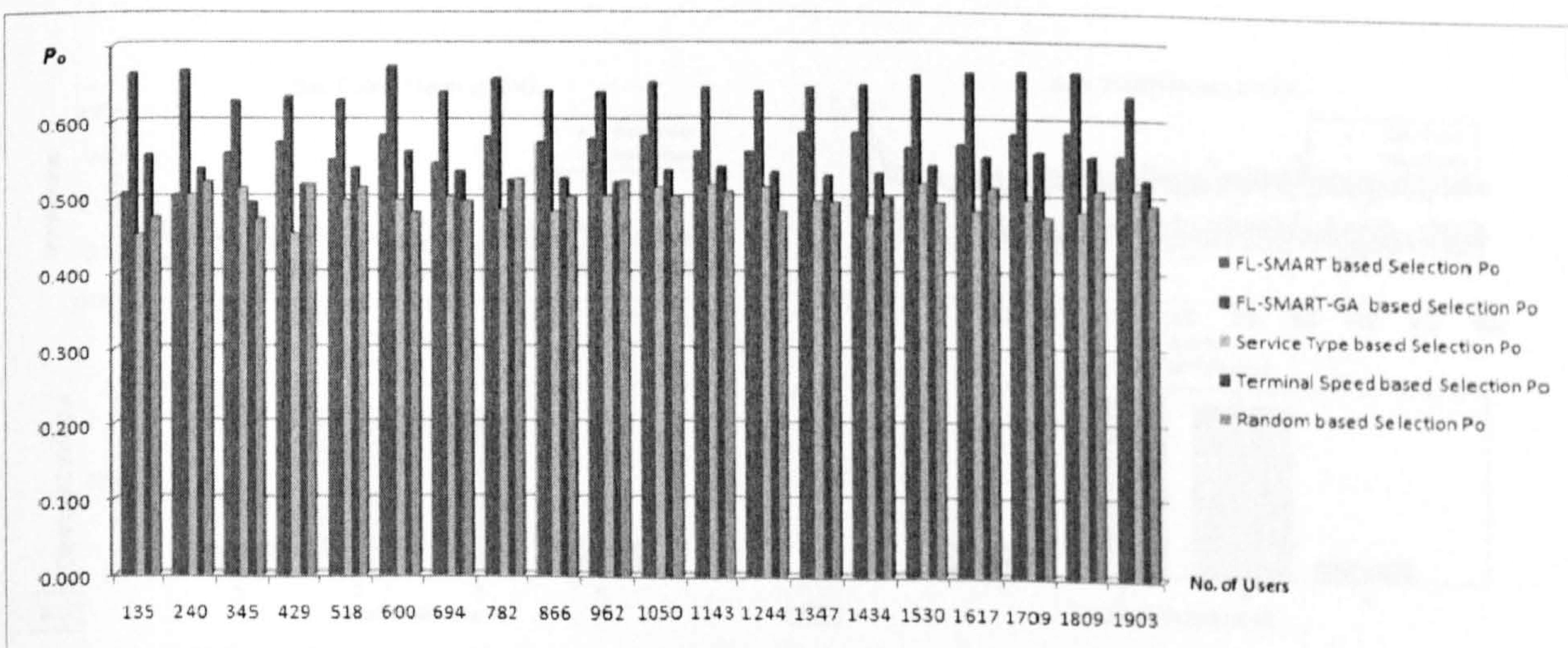

Figure 7.14: P_o values of the combined FL and SMART based algorithms against the reference algorithms

Table 7.5: P_o values of the combined FL and SMART based algorithms against the reference algorithms

No. of Users	FL-SMART selection P_o	FL-SMART-GA selection P_o	Service type selection P_o	Terminal-speed selection P_o	Random selection P_o
135	0.507	0.663	0.452	0.556	0.474
345	0.558	0.628	0.513	0.493	0.472
429	0.573	0.634	0.452	0.517	0.517
518	0.550	0.629	0.496	0.539	0.514
600	0.582	0.672	0.497	0.560	0.480
782	0.580	0.656	0.483	0.523	0.524
866	0.571	0.639	0.482	0.525	0.501
1050	0.581	0.650	0.513	0.535	0.502
1143	0.559	0.644	0.517	0.540	0.508
1244	0.561	0.639	0.514	0.534	0.482
1347	0.586	0.645	0.496	0.529	0.494
1434	0.585	0.648	0.475	0.532	0.500
1617	0.569	0.664	0.483	0.553	0.515
1709	0.584	0.666	0.499	0.560	0.475
1809	0.585	0.665	0.483	0.554	0.511
1903	0.556	0.634	0.511	0.525	0.492

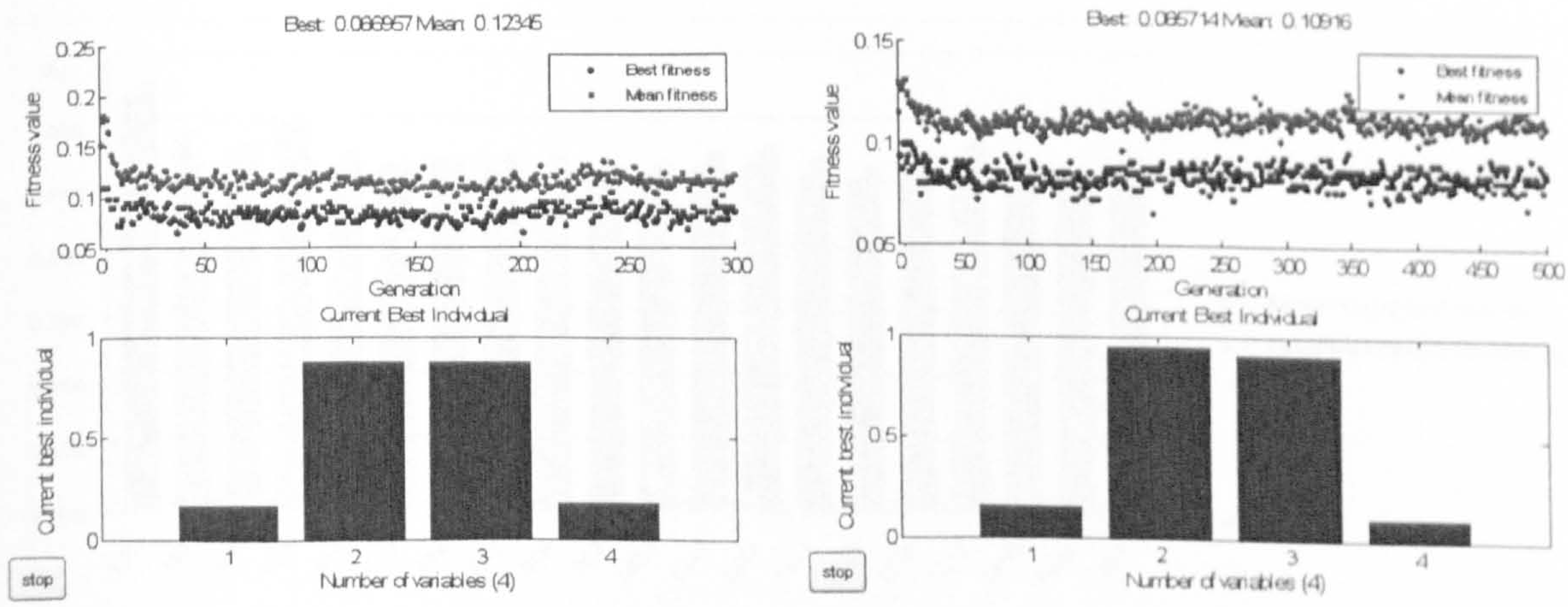

Figure 7.15: The weights assigned by GA for ObjFun3

7.4.4 P_q, P_u, and P_o Values using the Multi-objectives Function (ObjFun4)

To achieve better results in multi-objective manner, the ObjFun4 that has been developed in chapter 6 is used. If ObjFun4 with the three objectives of maximizing both P_q, P_u, and P_o is considered, the new results shown in figures 7.17, 7.16, and 7.18 and tables 7.7 , 7.6 and 7.8 are achieved.

From both Figure 7.16 and the numerical samples for P_q values shown in Table 7.6, the gain results from using optimal weights achieved by GA can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks with stronger signal in the non-optimized FL-SMART solution is 51.77% and it is 53.66% in the GA-optimized solution. In average, the GA-optimized solution achieves around 2% enhancement over the non-optimized solution in terms of the number of users with better signal conditions.

From both Figure 7.17 and the numerical samples for P_u values shown in Table 7.7, the gain results from using optimal weights achieved by GA can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks of their preferences in the non-optimized FL-SMART solution is 82.5% and it is 95.4% in the GA-optimized solution. In average, the GA-optimized solution achieves around 14% enhancement over the non-optimized solution in terms of the number of satisfied users.

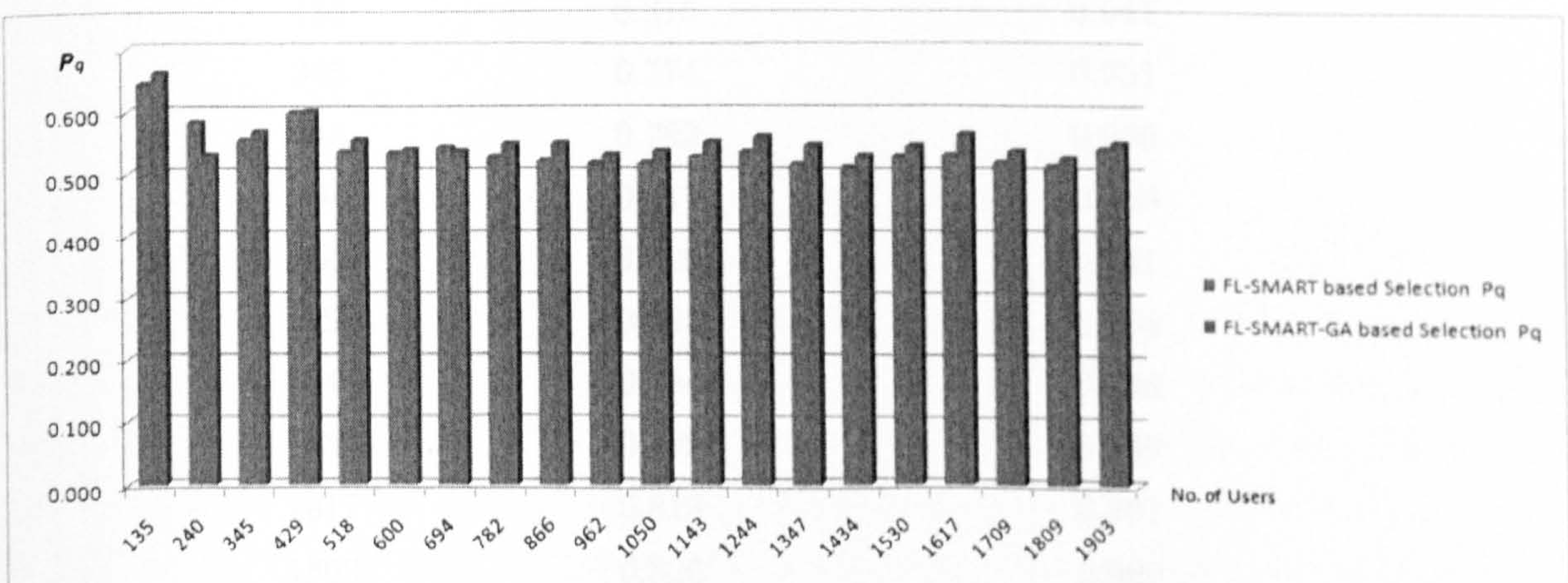

Figure 7.16: P_q values of the FL-SMART based selection algorithms using the weights achieved by ObjFun4

Table 7.6: P_q values of the FL-SMART based selection algorithms using the weights achieved by ObjFun4

No. of Users	FL-SMART selection P_q	FL-SMART-GA selection P_q
135	0.644	0.663
345	0.554	0.568
518	0.535	0.554
694	0.542	0.536
866	0.521	0.548
1050	0.517	0.536
1244	0.535	0.559
1434	0.511	0.529
1617	0.530	0.563
1809	0.512	0.525
1903	0.539	0.549

Table 7.7: P_u values of the FL-SMART based selection algorithms using the weights achieved by ObjFun4

No. of Users	FL-AHP selection P_u	FL-AHP-GA selection P_u
135	0.815	0.941
345	0.774	0.951
518	0.793	0.956
694	0.817	0.950
866	0.826	0.941
1050	0.825	0.954
1244	0.784	0.936
1434	0.799	0.939
1617	0.813	0.961
1809	0.826	0.960
1903	0.811	0.952

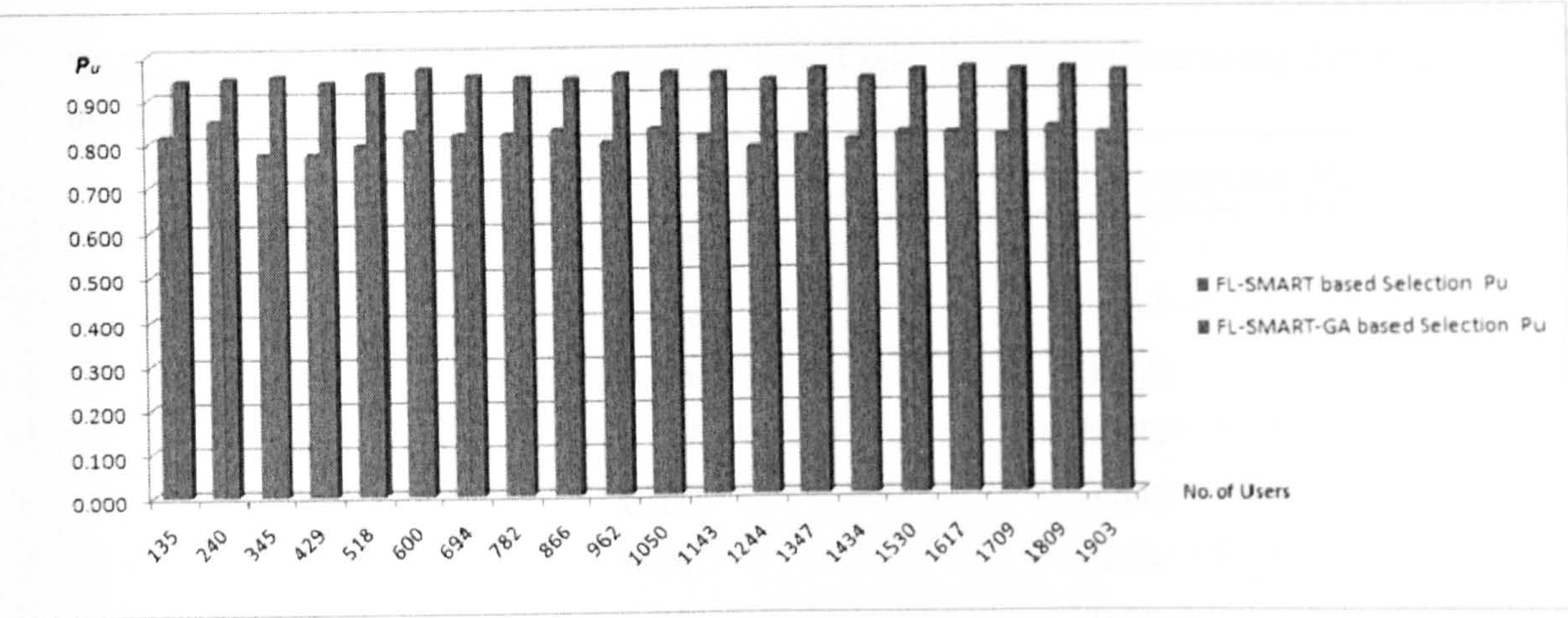

Figure 7.17: P_u values of the FL-SMART based selection algorithms using the weights achieved by ObjFun4

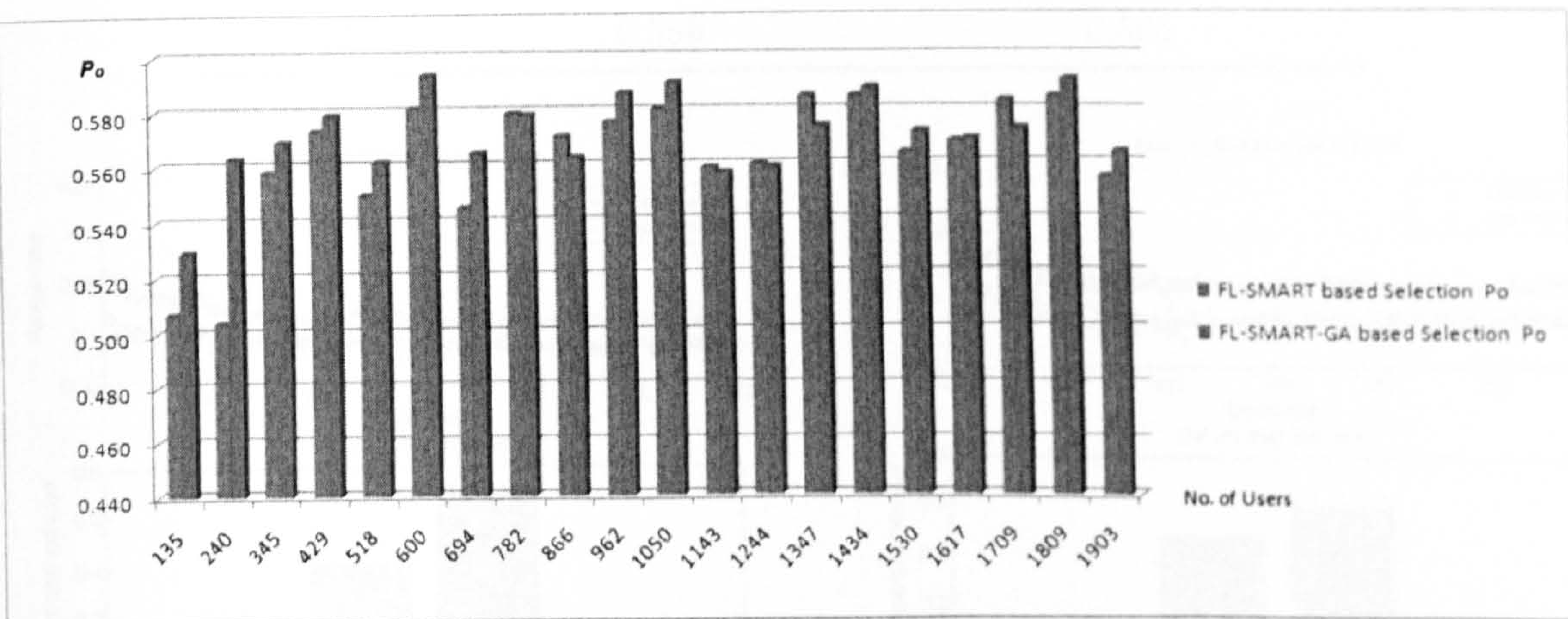

Figure 7.18: P_o values of the FL-SMART based selection algorithms using the weights achieved by ObjFun4

From both Figure 7.18 and the numerical samples for P_o values shown in Table 7.8, a small gain results from using optimal weights achieved by GA can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks with low-cost links in the non-optimized FL-SMART solution is 57% and it is 59% in the GA-optimized solution. In average, the GA-optimized solution achieves around 0.4% enhancement over the non-optimized solution in terms of P_o.

Figure 7.19 shows the achieved weights when the all three objectives are considered using the multi-objectives function ObjFun4. It shows that the GA gives low values for W_s and W_u and higher values for W_v and W_t.

Table 7.8: P_o values of the FL-SMART based selection algorithms using the weights achieved by ObjFun4

No. of Users	FL-AHP selection P_o	FL-AHP-GA selection P_o
135	0.507	0.53
345	0.558	0.569
518	0.550	0.562
694	0.545	0.565
866	0.571	0.563
1050	0.581	0.59
1244	0.561	0.56
1434	0.585	0.589
1617	0.569	0.57
1809	0.585	0.592
1903	0.556	0.565

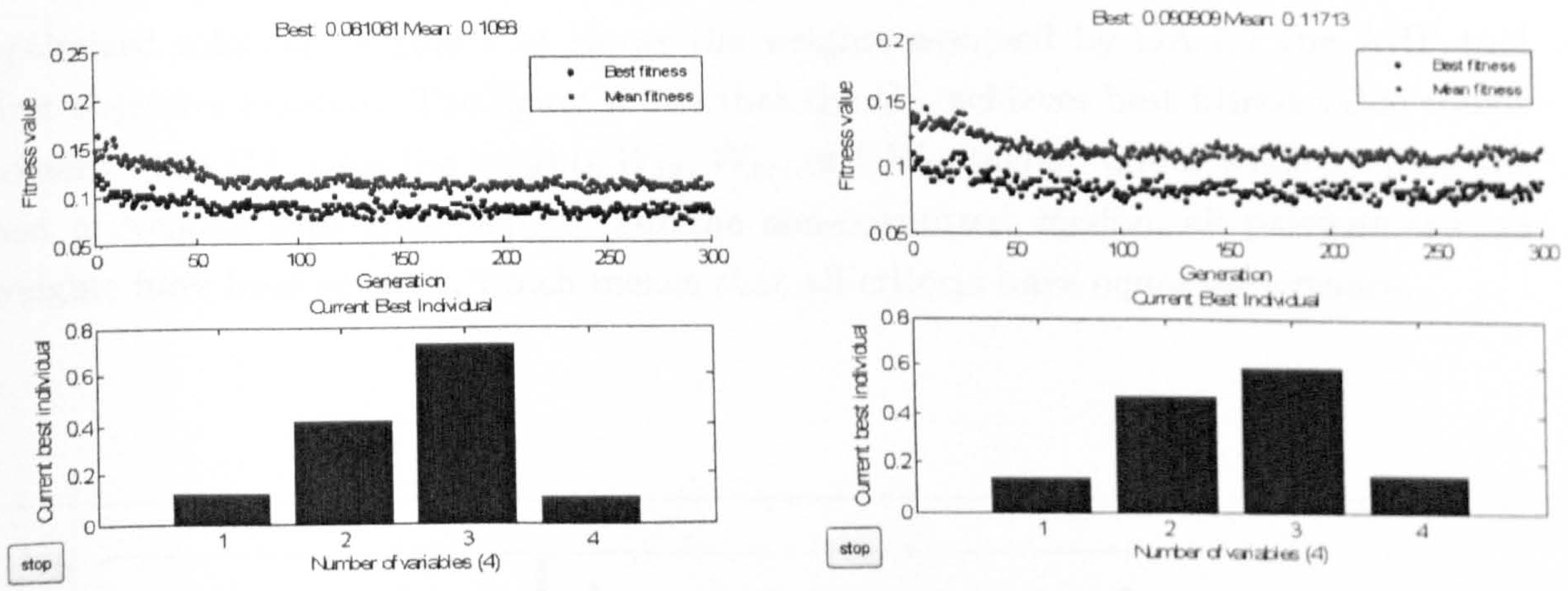

Figure 7.19: The weights assigned by GA for ObjFun4

7.5 The Performance Evaluation of the Combined FL and AHP Algorithms

Some simulation results for the developed algorithms in chapter 5 are presented and analyzed in this section. The achieved values of P_q, P_u, and P_o for our algorithms are compared with the values achieved by the reference algorithms.

7.5.1 Percentage of Users with Better QoS (P_q)

From both Figure 7.20 and the numerical samples for P_q values shown in Table 7.9, the improvement in the percentage of the users who are assigned to networks with stronger signal in our solutions can be seen. For example, with 1050 users, the percentage of satisfied users is 29.6%, 26.4%, and 32.5% in the service type based selection, the terminal-speed based selection, and the random-based selection respectively. The same percentage with the FL-AHP selection is around 38.1% and it is around 41.4% in the GA-optimized version. In average, our developed FL-AHP solution achieves around 4% enhancement over the service type and terminal-speed based selection algorithms. It also achieves around 2% enhancement over the random-based selection algorithm. The optimized FL-AHP solution achieves around 9% enhancement over the non-optimized version.

The weights achieved by AHP3RATObjFun1(see chapter 6) are used for the GA-optimized solution. Figure 7.21 shows the weights assigned by GA for the AHP tool first objective function. The figure shows that the GA achieves best fitness value equals to zero. The GA gives the weights W_{12}, W_{13}, and W_{14} higher values while keeping the rest of weights with lower values. For the non-optimized version, all pairwise criteria weights have been set to 1, which means that all criteria have equal importance.

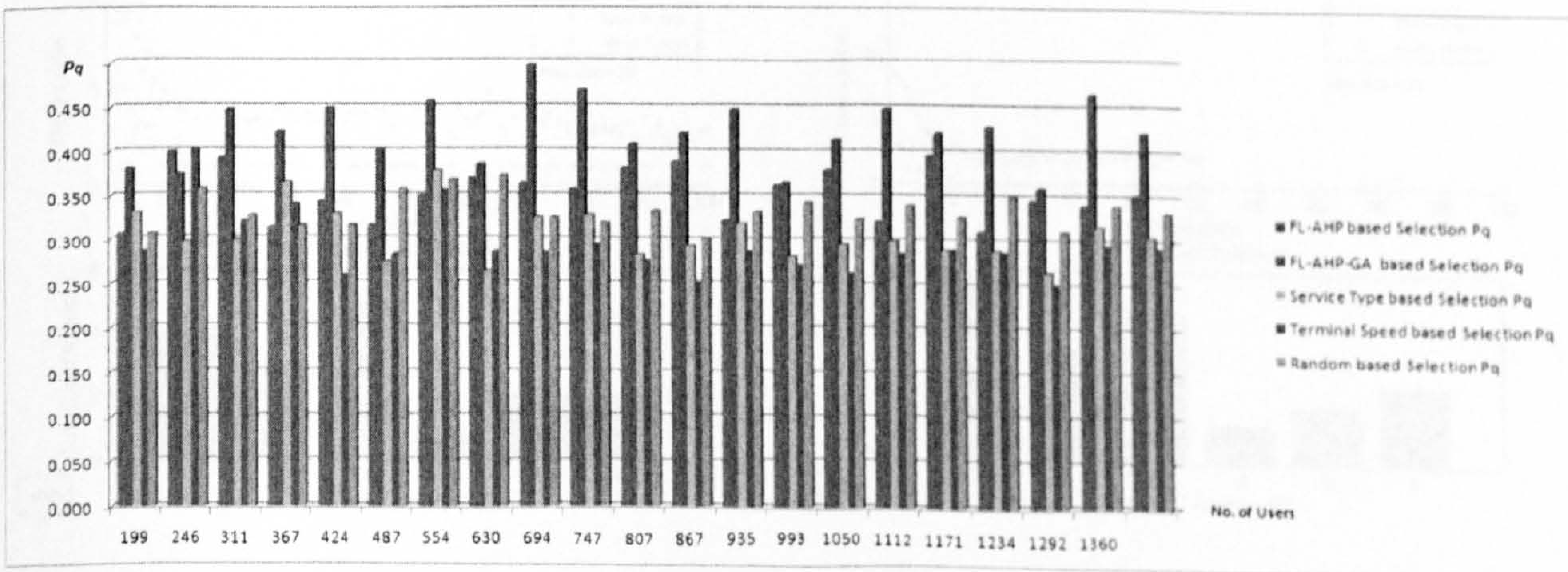

Figure 7.20: P_q values of the combined FL and AHP based algorithms against the reference algorithms

Table 7.9: P_q values of the combined FL and AHP based algorithms against the reference algorithms

No. of Users	FL-AHP selection P_q	FL-AHP-GA selection P_q	Service type selection P_q	Terminal-speed selection P_q	Random selection P_q
246	0.399	0.375	0.297	0.402	0.358
367	0.313	0.422	0.365	0.341	0.328
424	0.343	0.449	0.330	0.259	0.316
554	0.350	0.457	0.379	0.356	0.357
630	0.370	0.386	0.265	0.286	0.368
694	0.364	0.498	0.326	0.285	0.373
807	0.382	0.409	0.284	0.276	0.320
867	0.389	0.421	0.294	0.250	0.333
935	0.322	0.448	0.319	0.288	0.333
993	0.362	0.365	0.283	0.273	0.343
1050	0.381	0.414	0.296	0.264	0.325
1112	0.322	0.449	0.300	0.286	0.341
1171	0.396	0.421	0.290	0.290	0.327
1292	0.346	0.360	0.266	0.251	0.312
1360	0.342	0.465	0.317	0.296	0.341

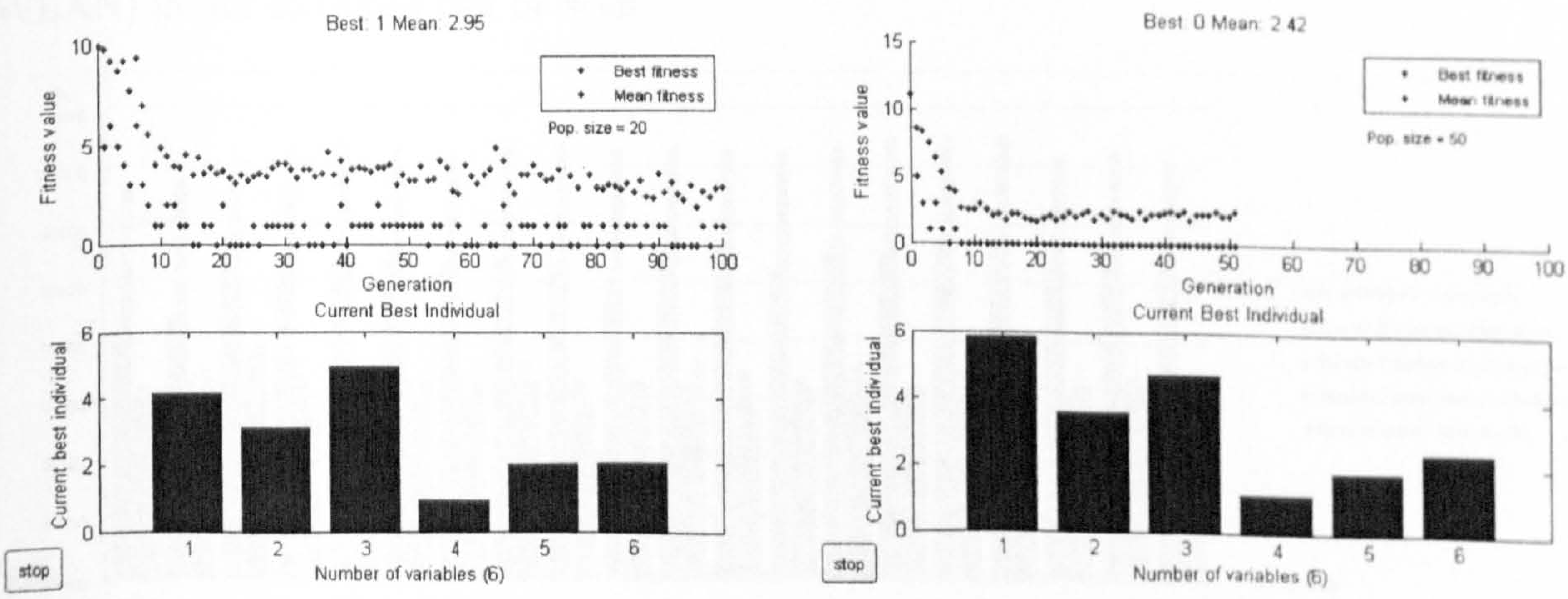

Figure 7.21: The weights assigned by GA for AHP3RATObjFun1

7.5.2 Percentage of Satisfied Users (P_u)

From both Figure 7.22 and the numerical samples for P_u values shown in Table 7.10, the great improvement in the number of the satisfied users in our solutions can be seen. For example, with 1050 users, the percentage of satisfied users is 32.5%, 33.3%, and 32.3% in the service type based selection, the terminal-speed based selection, and the random-based selection respectively. The same percentage in the combined FL and AHP is around 55.6% and around 75% in the GA-optimized version. In average, our developed FL-AHP solution achieves around 21% enhancement over the different reference algorithms. The optimized FL-AHP solution achieves around 40% enhancement over the different reference algorithms and around 19% over the non-optimized version.

The weights achieved by AHP3RATObjFun2 are used for the GA optimized solution. Figure 7.23 shows the weights assigned by GA for the AHP second objective function. The figure shows that the GA achieves best fitness value equals to zero. It gives the weights W_{12} and W_{23} high values while keeping the rest of the weights with minimum values.

7.5.3 Percentage of Users assigned to Low Cost Networks (P_o)

From both Figure 7.24 and the numerical samples for P_o values shown in Table 7.11, the improvement in the percentage of the users who are assigned to low-cost networks (i.e. WLAN) in our solutions can be seen.

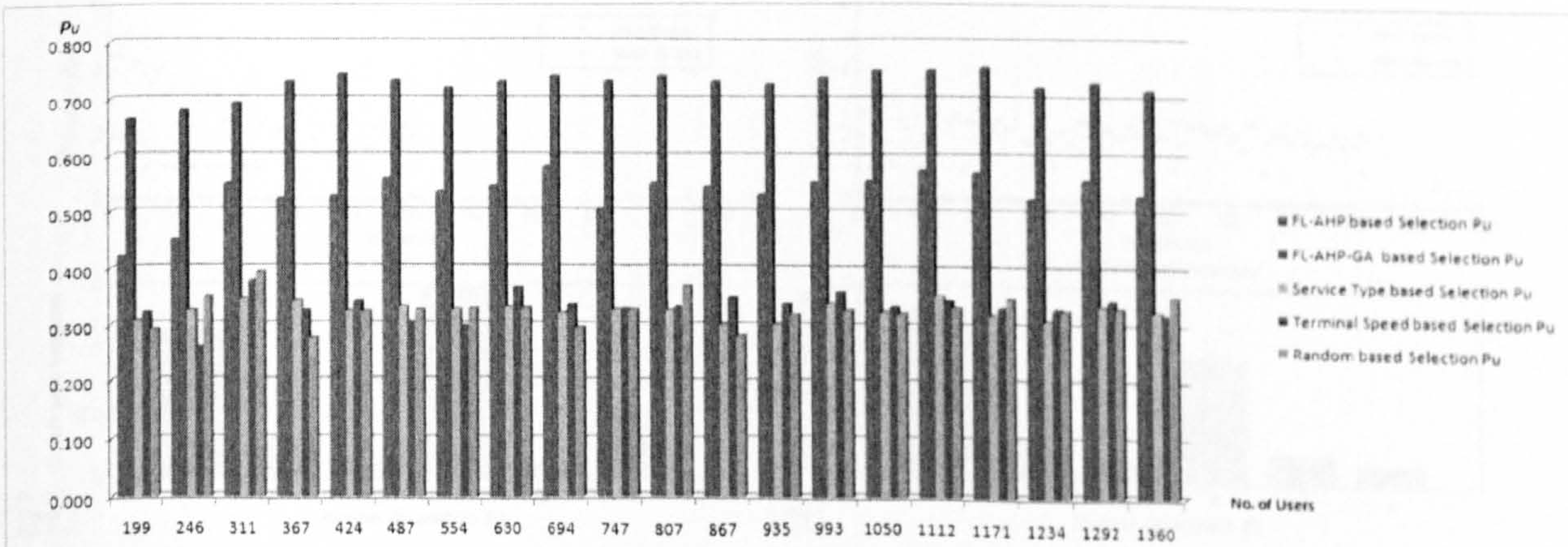

Figure 7.22: P_u values of the combined FL and AHP based algorithms against the reference algorithms

Table 7.10: P_u values of the combined FL and AHP based algorithms against the reference algorithms

No. of Users	FL-AHP selection P_u	FL-AHP-GA selection P_u	Service type selection P_u	Terminal-speed selection P_u	Random selection P_u
246	0.451	0.679	0.325	0.260	0.350
311	0.550	0.691	0.347	0.376	0.392
367	0.523	0.730	0.343	0.324	0.278
424	0.528	0.743	0.323	0.342	0.323
554	0.536	0.720	0.327	0.298	0.329
630	0.546	0.730	0.332	0.365	0.330
694	0.579	0.739	0.321	0.336	0.295
807	0.551	0.740	0.326	0.332	0.371
867	0.546	0.730	0.302	0.351	0.283
935	0.532	0.725	0.303	0.339	0.320
993	0.554	0.737	0.339	0.360	0.328
1050	0.556	0.750	0.325	0.333	0.323
1112	0.576	0.751	0.354	0.345	0.333
1171	0.572	0.756	0.320	0.332	0.350
1292	0.559	0.729	0.337	0.347	0.334
1360	0.532	0.717	0.328	0.323	0.355

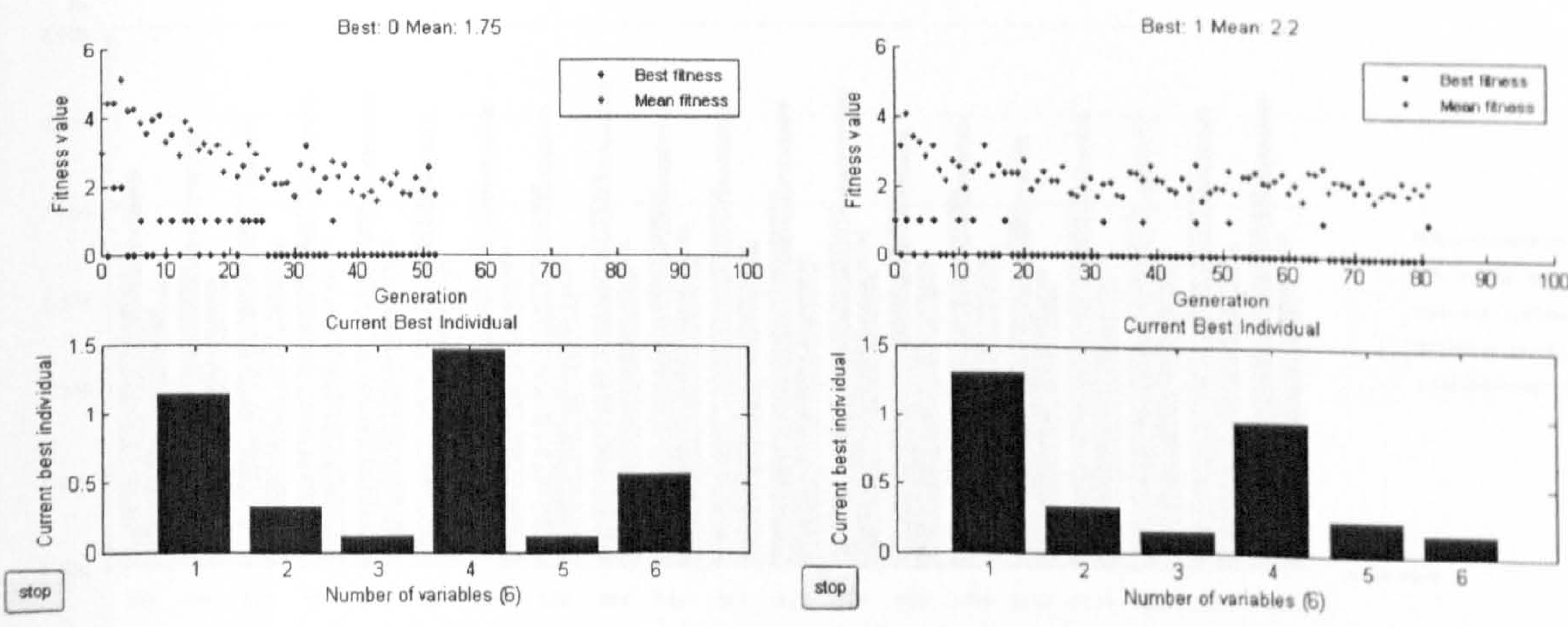

Figure 7.23: The weights assigned by GA for AHP3RATObjFun2

For example, with 1050 users in the environment, the percentage of the users who are assigned to the low-cost network is 25.1%, 34.1%, and 35.3% in the service type based selection, the terminal-speed based selection, and the random-based selection respectively. The same percentage with the combined FL and AHP is around 41.9% and it is around 49.8% in our GA-optimized solution. In average, our developed FL-AHP solution achieves around 16% enhancement over the service type based selection and around 8% over both the terminal-speed based selection and the random-based selection algorithms. The optimized FL-AHP version achieves around 10% enhancement over the non-optimized FL-AHP solution.

The weights achieved by AHP3RATObjFun3 are used for the GA-optimized solution. Figure 7.25 shows the weights assigned by GA for the AHP tool second objective function. The figure show that the GA achieves best fitness value equals to zero. The GA gives the weights W_{12} and W_{13} low values, the weights W_{14}, W_{23} and W_{34} medium values and the weight W_{34} high value.

7.5.4 P_q, P_u, and P_o Values using the Multi-objectives Function ObjFun4

To achieve better results in multi-objective manner, the ObjFun4 that has been developed in chapter 6 is used. If the ObjFun4 with the objectives of maximizing P_q, P_u, and P_o is considered, the new results that are shown in figures 7.26, 7.27, and 7.28 and

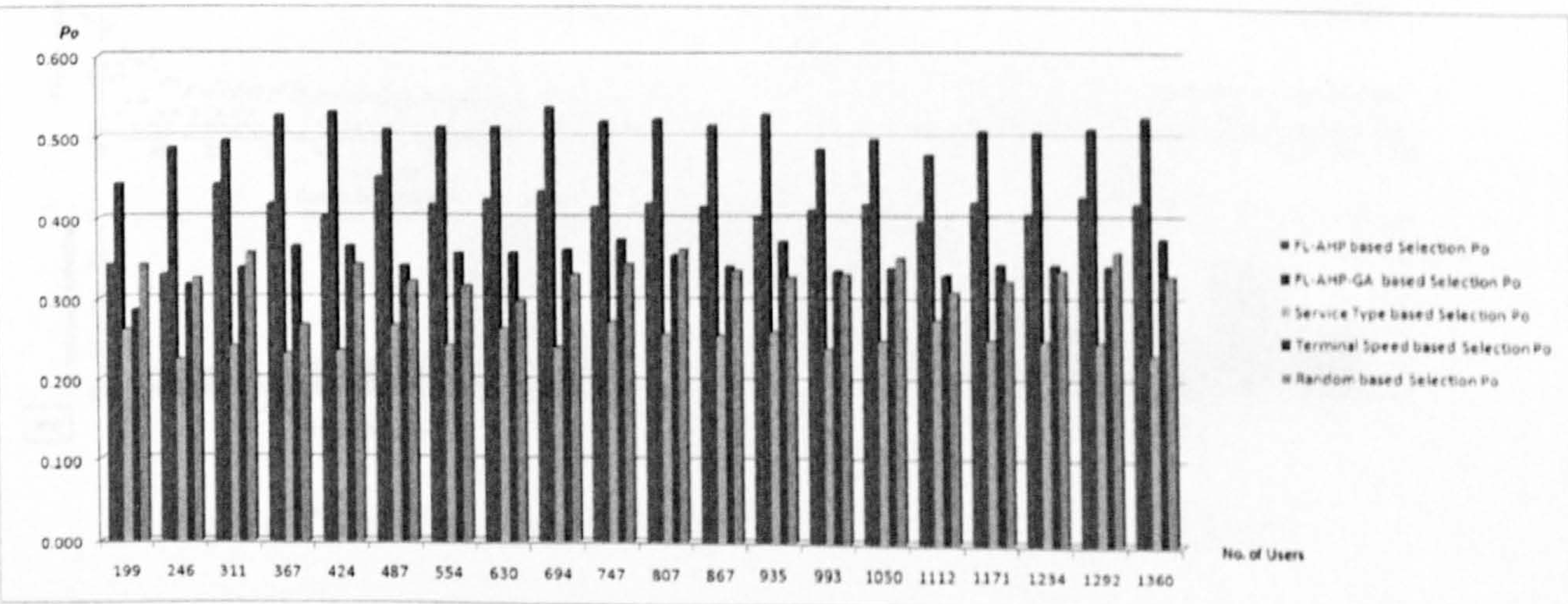

Figure 7.24: P_o values of the combined FL and AHP based algorithms against the reference algorithms

Table 7.11: P_o values of the combined FL and AHP based algorithms against the reference algorithms

No. of Users	FL-AHP selection P_o	FL-AHP-GA selection P_o	Service type selection P_o	Terminal-speed selection P_o	Random selection P_o
246	0.329	0.486	0.224	0.317	0.325
311	0.441	0.495	0.241	0.338	0.357
424	0.401	0.529	0.236	0.366	0.342
487	0.450	0.509	0.267	0.341	0.322
554	0.417	0.512	0.244	0.357	0.318
630	0.424	0.513	0.265	0.359	0.300
694	0.434	0.537	0.242	0.363	0.331
807	0.420	0.523	0.258	0.356	0.363
867	0.415	0.515	0.257	0.343	0.338
935	0.403	0.528	0.262	0.373	0.329
993	0.411	0.486	0.241	0.337	0.333
1050	0.419	0.498	0.251	0.341	0.353
1112	0.397	0.479	0.277	0.333	0.312
1171	0.421	0.507	0.253	0.345	0.325
1292	0.428	0.510	0.249	0.343	0.359
1360	0.419	0.524	0.234	0.376	0.331

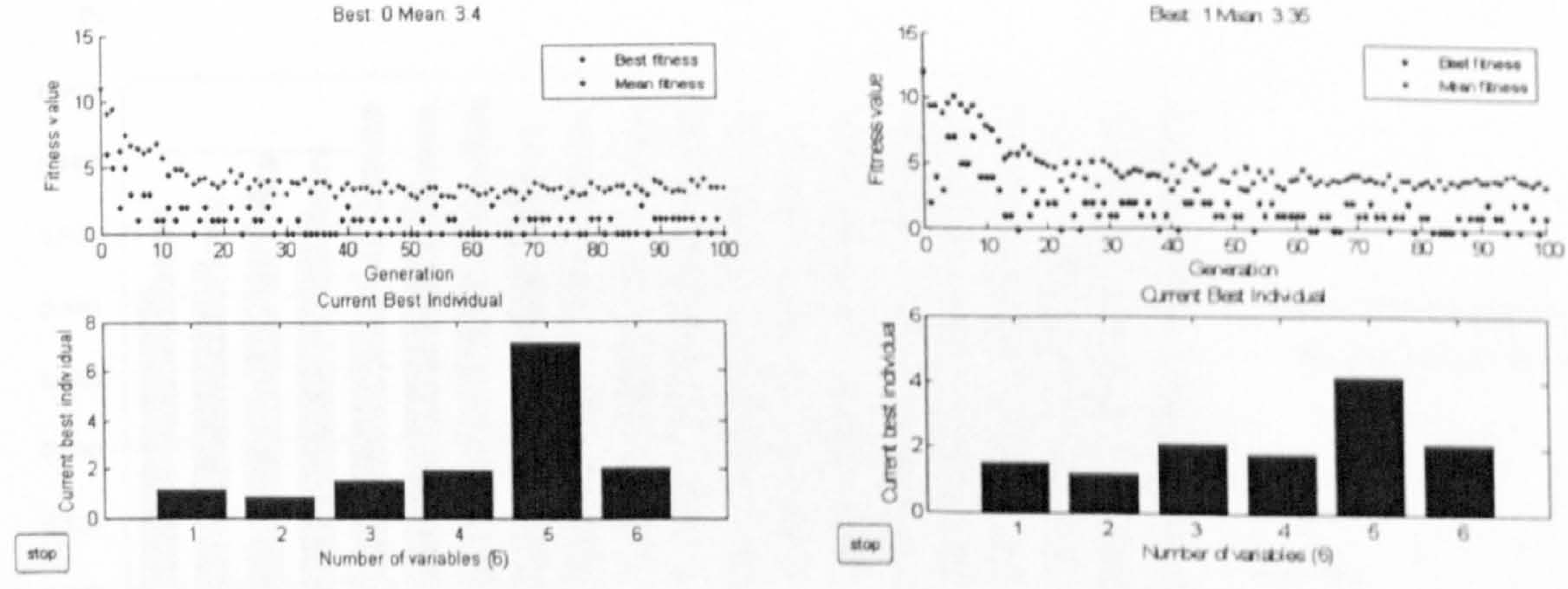

Figure 7.25: The weights assigned by GA for AHP3RATObjFun3

tables 7.13, 7.12, and 7.14 are achieved.

From both Figure 7.26 and the numerical samples for P_u values shown in Table 7.12,

Table 7.12: P_u values of the combined FL and AHP based selection algorithms using the weights achieved by ObjFun4

No. of Users	FL-AHP based Selection P_u	FL-AHP-GA based Selection P_u
246	0.451	0.541
367	0.523	0.610
487	0.559	0.661
630	0.546	0.640
747	0.505	0.661
867	0.546	0.656
1050	0.556	0.658
1112	0.576	0.675
1234	0.524	0.634
1360	0.532	0.659

the gain results from using optimal weights achieved by the GA multi-objective function ObjFun4 can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks of their preferences in the non-optimized FL-AHP solution is 55.6% and it is 65.8% in the GA-optimized solution. In average, the GA-optimized solution achieves around 11% enhancement over the non-optimized solution in terms of the number of satisfied users.

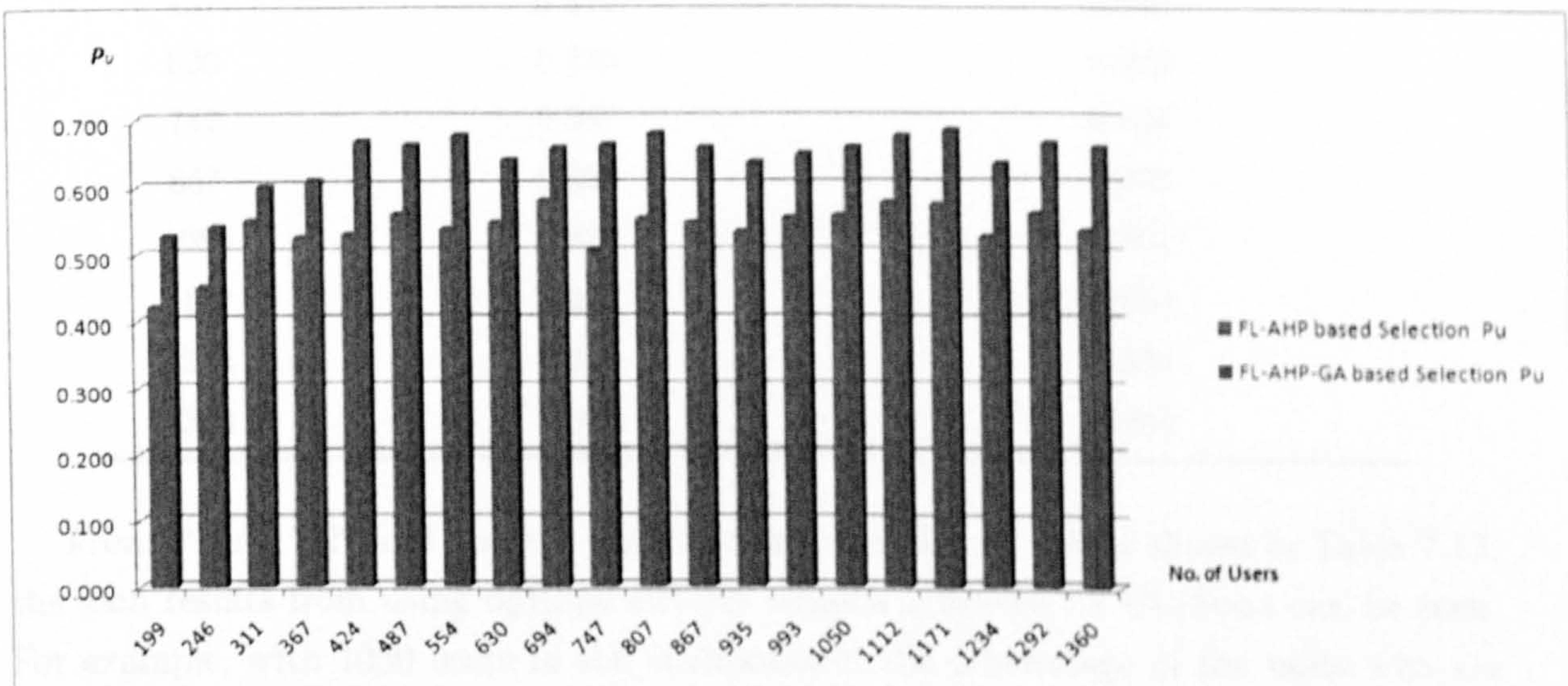

Figure 7.26: P_u values of the combined FL and AHP based selection algorithms using the weights achieved by ObjFun4

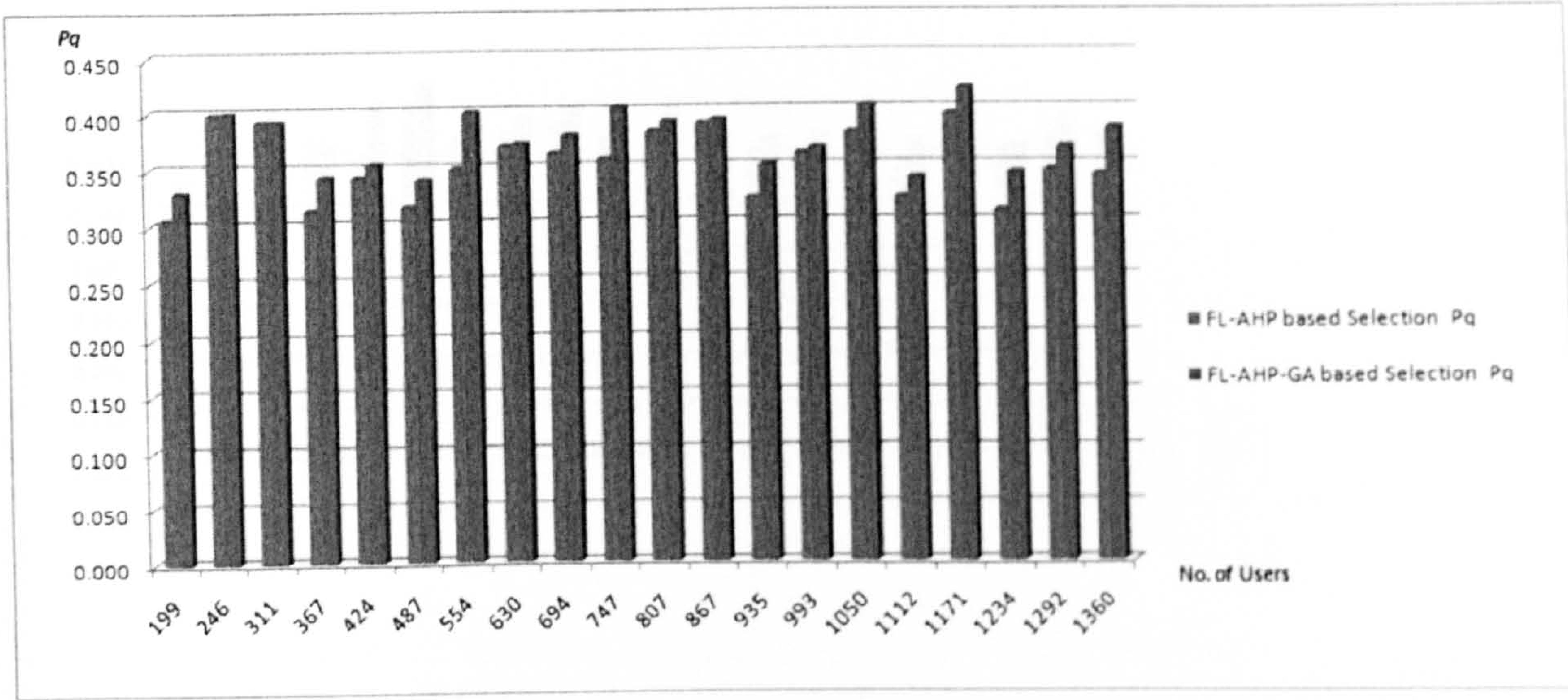

Figure 7.27: P_q values of the combined FL and AHP based selection algorithms using the weights achieved by ObjFun4

Table 7.13: P_q values of the combined FL and AHP based selection algorithms using the weights achieved by ObjFun4

No. of Users	FL-AHP based Selection P_q	FL-AHP-GA based Selection P_q
246	0.399	0.400
367	0.313	0.343
487	0.316	0.340
630	0.370	0.372
747	0.357	0.404
867	0.389	0.393
1050	0.381	0.404
1112	0.322	0.340
1234	0.311	0.344
1360	0.342	0.384

From Figure 7.27 and and the numerical samples for P_q values shown in Table 7.13, the gain results from using optimal criteria weights achieved by ObjFun4 can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks with stronger signal in the non-optimized FL-AHP solution is 38.1% and it is 40.4% in the GA-optimized solution. In average, the GA-optimized solution achieves around 2% enhancement over the non-optimized solution in terms of the number of users with better signal conditions.

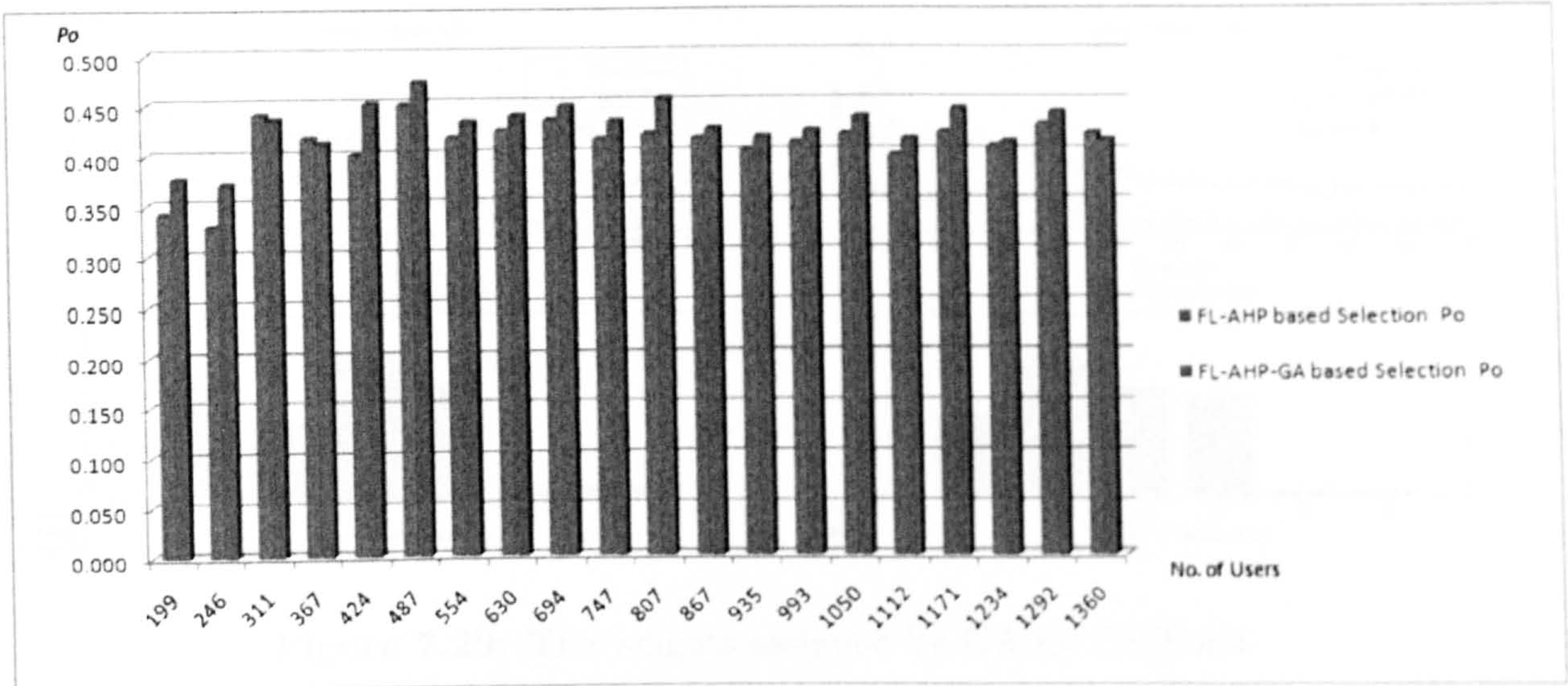

Figure 7.28: P_o values of the combined FL and AHP based selection algorithms using the weights achieved by ObjFun4

Table 7.14: P_o values of the combined FL and AHP based selection algorithms using the weights achieved by ObjFun4

No. of Users	FL-AHP based Selection P_o	FL-AHP-GA based Selection P_o
246	0.329	0.371
367	0.417	0.412
487	0.450	0.473
630	0.424	0.439
747	0.415	0.433
867	0.415	0.425
1050	0.419	0.437
1112	0.397	0.414
1234	0.406	0.411
1360	0.419	0.412

From Figure 7.28 and and the numerical samples for P_o values shown in Table 7.14, the gain results from using optimal criteria weights achieved by ObjFun4 can be seen. For example, with 1050 users in the environment, the percentage of the users who are assigned to networks low-cost links in the non-optimized FL-AHP solution is 41.9% and 43.7% in the GA-optimized solution. In average, the GA-optimized solution achieves around 1.5% enhancement over the non-optimized solution.

Figure 7.29 shows the weights assigned by GA for the AHP forth objective function.

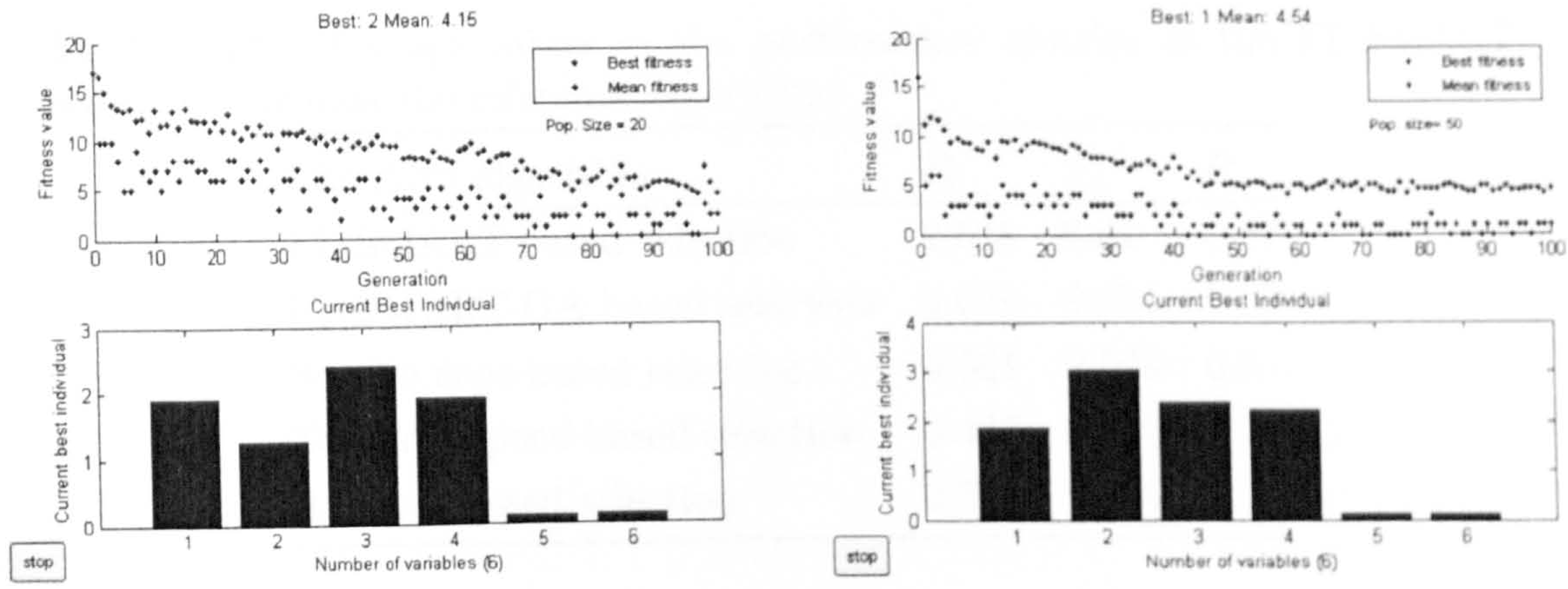

Figure 7.29: The weights assigned by GA for ObjFun4

The figure shows that the GA achieves best fitness value equals to one. GA gives the weights W_{12}, W_{13}, W_{14} and W_{23} high values.

7.6 Discussion

The simulation results that have been presented in the above two sections illustrate that our algorithms (that are developed in chapters 4 and 5 and their optimized versions in chapter 6) outperform the reference algorithms in terms of the percentage of satisfied users, the percentage of users with better quality conditions and in terms of the percentage of the usage of low-cost links.

Table 7.15 shows the average values (arithmetic means) of the different performance metrics in our FL-SMART algorithms with comparison to the reference algorithms. The table shows a great enhancement in our algorithms performance in terms of number of satisfied users (i.e. P_u) and smaller enhancements in terms of number of users with better QoS conditions (i.e. P_q) and number of users with low-cost links (i.e. P_o). The GA-optimized version usually achieve much better results than the non-optimized version.

Table 7.16 shows the average values (arithmetic means) of the different performance metrics in our FL-AHP algorithms with comparison to the reference algorithms. The table shows great enhancements in our algorithms performance in terms of number of satisfied users (i.e. P_u) and in terms of number of users with low-cost links (i.e. P_o) and a smaller enhancement in terms of number of users with better QoS conditions (i.e. P_q).

Table 7.15: Average values of the performance metrics in the FL-SMART algorithms against the reference algorithms

The ANS algorithm	P_q	P_u	P_o
FL-SMART based selection	0.528	0.81	0.57
FL-SMART-GA based selection	0.628	0.954	0.65
Service type based selection	0.501	0.503	0.5
Terminal-speed based selection	0.466	0.505	0.54
Random-based selection	0.500	0.496	0.5

Table 7.16: Average values of the performance metrics in the FL-AHP algorithms against the reference algorithms

The ANS algorithm	P_q	P_u	P_o
FL-AHP based selection	0.353	0.544	0.415
FL-AHP-GA based selection	0.424	0.732	0.509
Service type based selection	0.302	0.326	0.252
Terminal-speed based selection	0.286	0.336	0.351
Random-based selection	0.33	0.33	0.33

The GA-optimized versions usually achieve much better results than the non-optimized version.

To check the spread of the results around the average values, the standard deviations are used [151,152]. After calculating the standards deviations for all sets of achieved results, we have noticed that, they are very low (the maximum standard deviation does not exceed 0.04), which means that the performance does not change so much and keep performing around the average values. Consequently, stable performance metrics values are usually expected.

In one hand and for reasons of simplicity and computational complexity, the simulation cannot be carried out at higher number of users. In the other hand, although the achieved simulation results show that our algorithms outperform the reference algorithms, no clear monotonic decreasing or increasing relationship could be directly observed between the number of users and the performance metrics. To check if there is any linear relationship between the number of users and the achieved performance metrics, the Pearson's Correlation Coefficient (PCC) [151,152] is used. PCC investigates the strength and direction of a linear relationship between two random variables. PCC = +1 means very strong positive linear relationship. PCC = -1 means very strong negative linear relationship. PCC = 0 means no linear relationship is existed between both variables.

Table 7.17 shows the PCC values that refelct the relationship between the performance metrics and the number of users in the FL-SMART and reference algorithms. It is clear from the PCC values that, there is not strong linear relationship between the different performance metrics and the number of users in the different algorithms. However, we could notice that with very high number of users, the P_q values in FL-SMART algorithms is going down. On the other hand, with higher number of users the P_u and P_o values are expected to be better.

Table 7.18 shows the PCC values that refelct the relationship between the performance metrics and the number of users in the FL-AHP and reference algorithms. It is clear from the PCC values that, there is not strong linear relationship between the different performance metrics and the number of users in the different algorithms. However, we could notice that with very high number of users, the P_u and P_o values are expected to be better in FL-AHP algorithms. On the other hand, with higher number of users, the P_q values are expected to be stable and around the average value.

The mentioned expectations about the values of the P_q, P_u, and P_o are based on the calculations of PCC. PCC performs weak when no clear linear relationship is existed. As a result, we also calculate another type of correlation coefficient called Spearman's Correlation Coefficient (SCC) [151, 152]. Unlike the PCC, SCC does not require the assumption that the relationship between the variables is linear.

Table 7.17: PCC between the performance metrics and the number of users in the FL-SMART and reference algorithms

Algorithm/PCC	PCC of P_q	PCC of P_u	PCC of P_o
FL-SMART based selection	-0.667	0.066	0.556
FL-SMART-GA based selection	-0.36	0.157	0.158
Service type based selection	-0.236	-0.314	0.281
Terminal-speed based selection	-0.6	0.407	0.278
Random-based selection	-0.216	0.185	-0.025

Table 7.18: PCC between the performance metrics and the number of users in the AHP-SMART and reference algorithms

Algorithm/PCC	PCC of P_q	PCC of P_u	PCC of P_o
FL-AHP based selection	-0.007	0.553	0.335
FL-AHP-GA based selection	0.067	0.561	0.218
Service type based selection	-0.381	-0.035	0.202
Terminal-speed based selection	-0.503	0.284	0.306
Random-based selection	-0.0198	0.153	0.22

Table 7.19: SCC between the performance metrics and the number of users in the FL-SMART and reference algorithms

Algorithm/SCC	SCC of P_q	SCC of P_u	SCC of P_o
FL-SMART based selection	-0.6383	0.0218	0.4889
FL-SMART-GA based selection	-0.2031	0.2762	0.1657
Service type based selection	-0.1701	-0.2175	0.1818
Terminal-speed based selection	-0.6031	0.2959	0.195
Random-based selection	-0.2696	-0.0997	-0.0692

Both Table 7.19 and Table 7.20 show that, there is not strong non-linear relationship between the different performance metrics and the number of users in the different algorithms. This confirms the expectations of the PCC values in tables 7.17 and 7.18. Again, because of the positive values of SCC, we can expect better P_o and P_u values and worse P_q values with higher number of users in our developed algorithms.

Table 7.20: SCC between the performance metrics and the number of users in the FL-AHP and reference algorithms

Algorithm/SCC	SCC of P_q	SCC of P_u	SCC of P_o
FL-AHP based selection	-0.0338	0.4351	0.1159
FL-AHP-GA based selection	0.0843	0.3298	0.0391
Service type based selection	-0.4069	-0.0226	0.1572
Terminal-speed based selection	-0.284	0.2422	0.1941
Random-based selection	0.0263	0.2838	0.1355

At the end of this discussion, we can define the total performance (P_t) as a simple metric that reflects the whole performance of the algorithm according to equation 7.5

$$P_t = \frac{w_{pq} \cdot P_q + w_{pu} \cdot P_u + w_{po} \cdot P_o}{3} \tag{7.5}$$

w_{pq}, w_{pu}, and w_{po} are the weights that reflect the importance of P_q, P_u, and P_o metrics respectively. If all metrics have the same importance then, the total performance metric (P_t) equation can be described as in equation 7.6.

$$P_t = \frac{P_q + P_u + P_o}{3} \tag{7.6}$$

Table 7.21 shows the P_t values of the reference algorithms against our FL-SMART algorithm. For instance, with 1050 users in the environment, the percentage of the users who get better total performance is 50%, 51%, and 48.4% in the service type based selection, the terminal-speed based selection, and the random-based selection respectively. The same percentage with the non-optimized FL-SMART solution is around 64.1%. In average, our non-optimized FL-SMART solution achieves around 14% enhancement over the different reference algorithms. The optimized versions of the FL-SMART solution usually outperform the non-optimized version.

Table 7.21 shows the P_t values of the reference algorithms against our FL-AHP algorithm. For instance, with 1050 users in the environment, the percentage of the users who get better total performance is 29.1%, 31.3%, and 33.4% in the service type based selection, the terminal-speed based selection, and the random-based selection. The same percentage with the combined FL and AHP is around 45.2%. In average, our non-optimized FL-AHP solution achieves around 14% enhancement over the service type based selection and around 10% over the terminal-speed based selection and the random-based selection algorithms. The optimized versions of the FL-AHP solution usually outperform the non-optimized version.

Table 7.21: P_t values of the combined FL and SMART based algorithm against the reference algorithms

No. of Users	FL-SMART selection P_t	Service type selection P_t	Terminal-speed selection P_t	Random selection P_t
135	0.656	0.499	0.504	0.491
345	0.629	0.513	0.495	0.503
518	0.626	0.500	0.499	0.506
694	0.635	0.500	0.500	0.496
866	0.639	0.488	0.506	0.496
1050	0.641	0.500	0.510	0.484
1244	0.627	0.496	0.495	0.495
1434	0.632	0.498	0.495	0.498
1617	0.637	0.502	0.502	0.495
1809	0.641	0.503	0.505	0.501
1903	0.635	0.494	0.503	0.502

Table 7.22: P_t values of the combined FL and AHP based algorithm against the reference algorithms

No. of Users	FL-AHP selection P_t	Service type selection P_t	Terminal-speed selection P_t	Random selection P_t
246	0.393	0.282	0.327	0.344
367	0.418	0.313	0.343	0.287
487	0.441	0.292	0.309	0.335
630	0.447	0.287	0.337	0.334
747	0.426	0.310	0.332	0.331
867	0.450	0.285	0.314	0.308
1050	0.452	0.291	0.313	0.334
1112	0.432	0.311	0.321	0.329
1234	0.414	0.284	0.321	0.340
1360	0.431	0.293	0.332	0.342

Chapter 8

Conclusions and Future Work

The significant conclusions of our research are discussed in this chapter. Several major areas and new directions of future research are also proposed.

8.1 Conclusions

A suitable design for the ANS algorithms is a highly important issue. Choosing the most suitable RAT for the new service request has considerable effects on the whole NGWN performance. The wrong selection can easily lead to many undesirable situations such as congested networks, unsatisfied users, bad service quality, and wasted networks resources. This thesis explores the issue of ANS in the HWN. It presents a new generic framework to solve the selection problems that utilizes the advantages and strengths of the parallel fuzzy logic decision making, the multiple criteria decision making and the genetic algorithms. Based on the developed framework, several novel ANS algorithms have been designed, implemented, simulated and evaluated. The developed ANS solutions attempt to increase the user satisfaction, the operator benefits, and the QoS.

Most of the previous works address the ANS as a single-criteria and single-objective problem, which is unrealistic and has certain conflicts with the multi-criteria and multi-objective nature of the ANS problem. The ANS is a multi-criteria problem where different sets of criteria that reflect the different conditions and measurements from the NGWN have to be considered. In addition, the ANS is a multi-objective problem since several conflict objectives for operators, users, and applications have to be satisfied. As a result, our developed algorithms are based on multiple criteria and objectives.

All the previous multi-criteria solutions do not address the roles of the different parties in the selection process and they do not provide a deployable and complete solution that could work in the NGWN environments. Practically, both user and operator want to control the process of the ANS and their roles have to be different according to the coupling degree between the co-existing RATs in the NGWN. New fair roles for the operators and the users in the ANS process have been suggested. The new roles satisfy the expected advantages of the NGWN for both users and operators. They increase both the operator benefits and users satisfaction and service personalization. In a non-coupled or a multi-operator loose-coupled NGWN, the user has the total right for controlling the selection decision using a network-assisted mobile-controlled ANS algorithm that resides in his/her terminal. In a single-operator loose-coupled or a tight-coupled NGWN, the ANS solution is divided into two modules. The first module uses a network-assisted mobile-controlled ANS algorithm that resides in the user terminal and the second module uses a mobile-assisted network-controlled ANS that resides in the CRRM entity. Both modules have to interact to make the final selection decision.

Most of the multi-criteria algorithms do not utilize the advantages of the AI tools to overcome the difficulties and complexities involved in the NGWN environments. Furthermore, they do not address suitable methods for finding suitable criteria weights. The existed FL based ANS suffer from scalability and complexity problems when more RATs or membership functions are added due to the expected huge number of complex inference rules. A generic and new AI-based framework to solve the ANS problem has been developed in this study. The developed framework utilizes the advantages of the parallel fuzzy logic, GA, and MCDM over the traditional methods. Our framework is a very promising solving scheme for any optimized selection problem in a changing environment such as the NGWN. It is a scalable and able to handle any number of RATs with a large set of criteria. The framework scheme can easily cope with the different viewpoints and goals of the operators and users. It can react to the accumulated human knowledge about the problem by adapting the MCDM weights or by tuning the FL membership functions and rules. It can handle the trade-off between the different criteria and assign suitable weights for each criterion according to its importance.

The developed framework has been used to present and design two novel network-controlled mobile-assisted operator ANS algorithms. The first algorithm is used in co-existing WWAN and WLAN environments and utilizes the SMART MCDM tool and Mamadani FIS. The second algorithm is used in co-existing WWAN, WLAN, and WMAN environments and utilizes the AHP MCDM tool and Sugeno FIS. In both algorithms, several considerations have been taken into account when designing and implementing the FL and MCDM systems to ensure simple and robust design. In this stage, the weights of the MCDM criteria have to be chosen manually based on the operator knowledge about the importance of each criterion.

The GA global search ability has been utilized to optimize the criteria weights and to help the operator to find the best weights according to his/her objectives. Our selection decision for GA was based on the nature of our objective functions that have several dynamic and stochastic components, where any other derivative-based optimization method cannot perform well. Another important issue that encourages the selection of GA to our problem was the high interaction between the different variables of an objective function. The GA is used with different objective functions to find out the best weights that could maximize (a) The number of users who are assigned to networks of their preferences, (b) The number of users who are assigned to networks with stronger signal, and/or (c) The number of users who are assigned to low-cost links. Several single-objective functions and one multi-objective function have been built to represent the different objectives. The main problem when working with GA is to select and set-up its parameters and operators. As a result, several tests have been carried out to check the best values and types for mutation rate, crossover rate, population size, selection function, mutation function, crossover function, and elitism count for the problem under consideration. We have found that these parameters and operators have different impacts on the GA performance. However, they are tightly dependent on the objective functions.

Our developed algorithms (both non-optimized and optimized versions) are simulated, evaluated, and compared with three reference algorithms. In average, our developed FL-SMART solution achieves around 3%, 30%, and 7% enhancements over the different reference algorithms in terms of number of users assigned into network with stronger signal (P_q), number of satisfied users (P_u), and number of users assigned into the low cost network (P_o) respectively. The optimized FL-SMART solution achieves around 10%, 15%, and 8% enhancements over the non-optimized FL-SMART solution in terms of P_q, P_u, and P_o respectively. In average, our developed FL-AHP solution achieves around 3%, 20%, and 8% enhancements over the different reference algorithms in terms of number of users assigned into network with stronger signal (P_q), number of satisfied users (P_u), and number of users assigned into the low cost network (P_o) respectively. The optimized FL-AHP solution achieves around 10%, 20%, and 8% enhancements over the non-optimized FL-AHP solution in terms of P_q, P_u, and P_o respectively.

The different algorithms have been simulated in twenty different numbers of users. Although our algorithms achieve good enhancement with respect to the different performance metrics, no clear monotonic decreasing or increasing relationship could be directly observed between the number of users and the performance metrics. Because it is too complex and meaningless to keep increasing the number of users in the simulation; we have used some statistical indicators such as the arithmetic means, standard deviations, and correlation coefficients to predict the behaviours of the algorithms on the future based on the achieved results. All the statistical indictors show that our algorithms will keep performing around the mean value of the achieved results. They also show that, it is expected to get better P_u and P_o and worse P_q values with very high number of users.

8.2 Future Work

Different aspects of our work can be further developed. Possible directions for further research are listed and briefly discussed here.

- **The user software assistant.** OSA based on different network-controlled terminal-assisted ANS algorithms is developed in this study. A User Software Assistant (USA) that is based on our developed framework can also be built. The USA can use a terminal controlled with network assistant ANS algorithms that use different subjective user criteria. In addition, the interaction between the USA and OSA to find the most optimal access network for both the user and operator can be considered.

- **Other optimization methods.** Other global search methods such as simulated annealing and heuristic random search can be used, evaluated and compared against the GA to optimize the criteria weights. Another possibility here is to use multi-objective optimization methods (such as the multi-objectives GA) to solve the conflicted objectives of the ANS problem.

- **The relationship between the initial ANS and the other CRRM and RRM mechanisms.** The developed ANS algorithms can be integrated with other CRRM mechanisms such as JAC, JCC, and VHO. A joint optimization of these mechanisms can enhance overall system performance. For example, ANS can help the JCC to reduce any possible congestion in the future by selecting the network with better resource availability.

- **The application of the developed ANS algorithms to specific standards.** This study has developed generic ANS algorithms. The algorithms can be tailored to specific wireless standards such as UMTS, IEEE802.16, and IEEE802.11.

- **The addition of more criteria.** In the developed ANS algorithms, more criteria can be included such as Resources Availability (RA) and Signal-to-Noise Ratio (SNR). Resource Availability (RA) is an important criterion that could be considered when accepting or rejecting the new or handoff service request. However, RA is usually considered at the admission and resource allocation stage by the local or common admission and load control algorithms. In fact, we think it would be more desirable to consider the RA criterion at both the initial selection stage and the resource allocation stage. In the initial selection stage, the network with more available resources has more credits to be selected for the new service request. In the resource allocation stage, the required resources for the new or handoff service are allocated from the low congested network.

- **The consideration of more realistic traffic models.** In our study no specific traffic models for packet based services are considered. This assumption does not affect the results of the initial ANS algorithms, because the initial ANS does not consider the resources allocation and network traffics issues. However, it will be more desirable to consider a wider variety of traffic conditions and mobility scenarios.

- **The building and tuning of rules and membership functions.** The used rules and membership functions of the fuzzy systems are still subjective, so they can be built or tuned using suitable learning methods such as the genetic algorithms or the neural networks.

- **More reference algorithms.** Our algorithm can be compared with more reference algorithms and especially with the widely used utility-function based algorithms.

- **The elimination factor.** A very nice idea that could be used to achieve a more scalable solution and accept more criteria and RATs is to use elimination factors. For example, in a co-existing WLAN, WMAN, and WWAN RATs, it is not practical to consider the WLAN as an option for a very fast user. In such case, the user velocity is used as the elimination factor that eliminates the WLAN from the considered RATs list. A list of elimination factors could be considered and the

RAT that could not achieve a minimum value for each factor is directly removed from the considered list of RATs.

- **The choices of the system models.** It is believed that different system models can produce a large impact on the results. Two different system models have been used in our study to give more creditability to our results, but more models can give more creditability.

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Appendix A

Types of Fuzzy Inference Systems

The Fuzzy Inference System (FIS) maps the input fuzzy sets into output fuzzy sets and handles the way in which the rules are combined just as humans use many different types of inferential procedures. The most common inference systems are the Mamdani FIS and the Sugeno FIS. These two types have been widely employed in various FL based applications. The differences between these two FIS lie in the consequents part of the fuzzy rules and the aggregation and defuzzification procedures.

A.1 The Mamdani FIS

Mamdani FIS was proposed in 1975 by Ebrahim Mamdani [129]. It consists of the four main parts that are described in chapter 2. The main difference between Mamdani FIS and other types of FIS systems is that it usually expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification process. A typical rule in a Mamdani fuzzy model has the form
If Input 1 = A and Input 2 = B, then Output is z = C
where all A, B, and C are linguistic variables to describe the membership degree of each variable.

The following are some important features for the Mamdani Method.

- It is intuitive and it allows us to describe the expertise in more human-like manner.
- It has widespread acceptance for capturing expert knowledge and well suited to

human input.

- It is flexible in terms of choosing the fuzzifier, fuzzy inference engine, and defuzzifier. As a result, it is efficient in obtaining the most suitable fuzzy logic system for a particular application.

- Mamdani-type fuzzy inference needs a substantial computational efforts and resources.

A.2 The Sugeno FIS

Sugeno or Takagi-Sugeno-Kang FIS was introduced in 1985 [130]. It is similar to the Mamdani method in many features. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. As a result, it avoids defuzzification because we get a crisp value in the output. A typical rule in a Sugeno fuzzy model has the form
If Input 1 = x and Input 2 = y, then Output is z = ax + by + c

For a zero-order Sugeno model, the output level z is a constant (i.e. a=b =0). A single spike (called a singleton), is used in the zero-order Sugeno model as the output membership function. A fuzzy singleton is a fuzzy set with a membership function that is unity (i.e. = 1) at a single particular point on the universe of discourse and zero everywhere else.

The following are some important features for the Sugeno Method.

- It is computationally efficient, because it avoids the complex defuzzification process required in Mamdani.

- Because it has a well-defined and compact output function, it works well with optimization and adaptive techniques.

- A weakness of Takagi-Sugeno fuzzy system is that the consequents part of its rules are not fuzzy, therefore, it does not provide an easy way to incorporate linguistic rules from human experts or operators.